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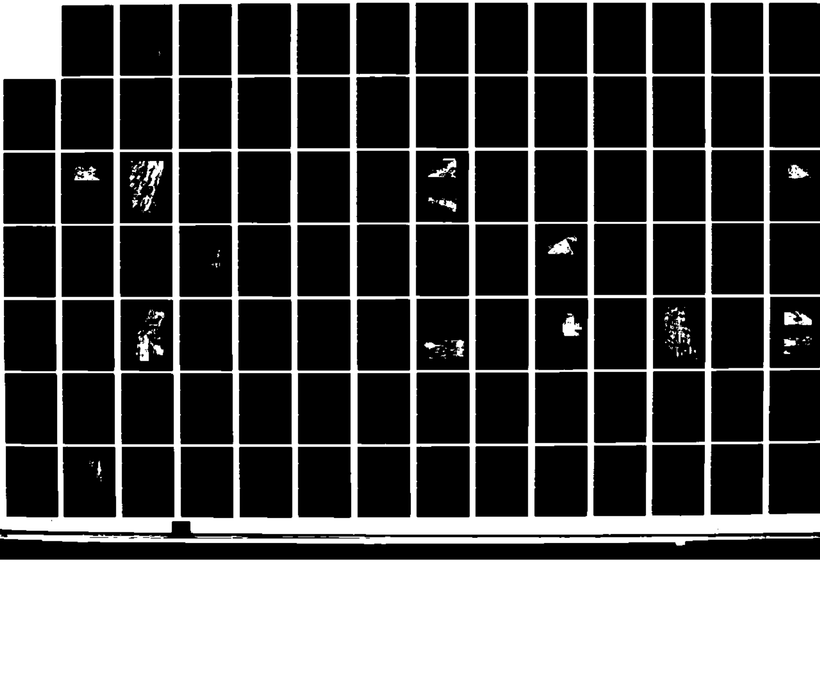

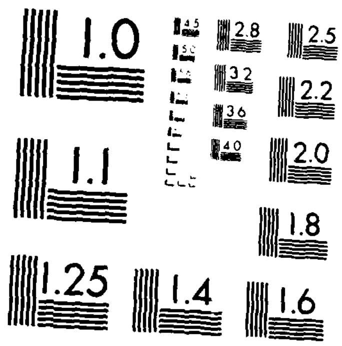

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Construction Materials for Coastal Structures

by

Moffatt and Nichol, Engineers

SPECIAL REPORT NO. 10

FEBRUARY 1983

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Prepared for

U.S. ARMY, CORPS OF ENGINEERS

COASTAL ENGINEERING
RESEARCH CENTER

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Construction materials	Protective coatings	Timber

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is a comprehensive report describing design properties of materials used in coastal protective structures and some harbor structures. The materials include stone, earth, concretes, asphalts, grouts, structural and sheet metals, wood, and plastics. The principal physical properties of these materials and their importance in the selection of materials for different types of projects are presented. The materials that have proved most effective and durable in coastal structures, such as stone, concrete, steel, and timber,

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are emphasized by detailed coverage of their properties. Synthetic materials used for geotextiles are described in detail also.

The report describes the effects of common forces encountered in the coastal environment on the materials' design properties. The effects of material placement, joining, and repair methods and of treatments to prolong design life are also presented. The report discusses in detail the impregnation of wood with preservatives and the cathodic protection and coating of metals. Example projects illustrate the use of the materials in breakwaters, jetties, groins, seawells, bulkheads, revetments, and harbor piers and wharves.

PREFACE

This report is published to provide coastal engineers with specific guidelines for selecting materials suitable for construction in the marine environment. The study is confined to the properties of these materials and treatments or variations thereof that are applicable to coastal engineering structures. The work was carried out under the U.S. Army Coastal Engineering Research Center's (CERC) Develop Functional and Structural Design Criteria work unit, Coastal Structure Evaluation and Design Program, Coastal Engineering Area of Civil Works Research and Development.

The report was prepared by Moffatt and Nichol, Engineers, under CERC Contract No. DACW72-80-C-0006. Preparation of the report was under the direction of L.L. Whiteneck, with assistance of L.A. Hockney and S.H. Anderson. Consultation and technical writing was provided by R.J. Barrett, A.L. Roebuck, C.M. Wakeman, W.J. Herron, Jr., and R.A. Morrison and L.J. Lee of Woodward and Clyde Consultants. Cooperation and assistance were provided by Corps of Engineers Divisions and Districts.

R.E. Ray was the CERC contract monitor for the report, under the supervision of Mr. R.A. Jachowski, former Chief of the Coastal Design Branch, and Mr. N. Parker, Chief, Engineering Development Division.

Technical Director of CERC was Dr. Robert W. Whalin, P.E.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

Ted E. Bishop

TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.
To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

CONSTRUCTION MATERIALS FOR COASTAL STRUCTURES

by
Moffatt and Nichol, Engineers

I. INTRODUCTION

1. General.

Construction materials for coastal structures may be classified into five general categories: stone and earth, concrete, metals, wood, and synthetics. Some of these categories are treated in more than one section in this report in order to better clarify their use and performance in different structures. For example, stone and earth are each discussed in separate sections, as are Portland cement and other types of concrete and grout. The material requirements are discussed in sufficient detail to permit the coastal engineer and structural designer to evaluate materials based on the physical properties of these materials and the past performance in coastal structures use. Coastal structures generally considered are breakwaters, groins, seawalls, bulkheads, revetments, jetties, piers, wharves, piles, and navigation aids, as well as other less common structures.

2. Background.

There have been a number of excellent coastal engineering manuals and guides that incorporate the best principles and criteria for design of coastal structures that have evolved through several decades of experience and research. However, most of these publications treat the subject of materials adequacy lightly. An in-depth coverage of the pros and cons of each material used would make these publications too unwieldy for efficient use. Thus the subject is usually covered by references to a number of disparate and often voluminous treatises on properties of materials, which places a heavy burden of literature research on the design professional. Many of these treatises cover aspects of the materials that have little relevance to coastal use in addition to information of value to the coastal engineer. In some cases, the reference may ignore unique effects of the coastal environment on the subject materials.

3. Objective.

The objective of this publication is to condense the subject of materials adequacy and suitability into a single document to support the coastal engineering profession while eliminating the superfluous coverage. The study is confined to the properties of those materials and treatments or variations thereof that are applicable to coastal engineering structures. Emphasis is placed on full coverage of materials that have proved most effective and long-lasting in coastal structures.

4. Organization of Report.

Experience has demonstrated the success and failure of many materials used in the past to create various types of coastal structures. In this report the principal physical properties of these materials and their importance in the selection of construction materials are set forth. New synthetic materials as

well as protective systems, including coatings and cathodic protection of metals, are included so that an evaluation of the long-term use of metals in the coastal zone can be considered in the material selection process. Problems associated with the use of different materials are discussed when considering their physical properties which may impact upon and establish a limited use for the material.

Section XII briefly discusses the significant uses of each material as well as some of the investigations and research that may improve the use of these materials in the coastal zone. The specific material section and the summary section will provide the coastal engineer with the fundamental physical properties information with which he must be concerned. Specific problems brought about by unusual or non-reoccurring local conditions may require further investigation or research to ascertain the potential performance of a given material in such a specific environment.

This publication is intended to assist the coastal engineer in the selection of appropriate materials for use in the coastal zone. While information is included on the placement of materials, their repair, and the treatment of materials to improve durability, this information should be considered as a guide and not definitive instructions for field use of the material. Professional personnel experienced in areas such as wood treatment, protective systems and cathodic protection should be consulted for implementation of design parameters presented in this manual.

II. MATERIAL REQUIREMENTS FOR COASTAL STRUCTURES

1. General.

Primary considerations in the selection of a material for coastal structures are availability, strength, durability, life of the material as compared to desired life of the structure, costs, and ease of maintenance as compared to maintenance costs. The selection of materials for coastal use must also consider the structural stability and flexibility. Also, depending on location, the impact of the environment on the material may be a determining factor.

2. Structural Properties.

a. Specific Gravity. This property must be considered if the material is to be placed in the water, on the ocean bottom, or on dryland, or is to be used as a floating structure. Rock and earth as well as concrete of high-specific gravity are a must for submerged structures, while floating structures must be of low-specific gravity materials such as wood and most synthetics. Heavy materials are used for floating structures only if the design provides for adequate buoyancy.

b. Material Strength. Material strength in tension, compression, and flexure may determine the size and stability of a structure. Most metals are high in tensile strength while unreinforced concrete is low in tensile but high in compressive strength. Rock and soils may be of high strength as individual pieces or particles but may require high strength adhesives to create an acceptable coastal structure.

c. Resistance to Cyclical and Impact Loading. Resistance to cyclical and impact loading, such as waves or coastal storm conditions, may require consideration of material flexibility within its elastic limit or the flexible limits of an adhesive used in the structure. For example, cement used in making concrete has virtually no flexibility while asphalt as a binder can be quite flexible.

d. Resistance to Seismic Forces. These forces, which can be both horizontal and vertical, may result in excessive structural stresses. Seismic forces may require a structure to be stiff and rigid, such as concrete or steel, or constructed of nonhomogeneous materials such that seismic forces can be relieved in planned isolated areas of the structure.

e. Material Flexibility. This property includes the ability to bend without breaking or to be adaptable to change in configuration. Wood has some degree of flexibility; rubber and certain synthetic materials have flexibility to a high degree. While structural steel is usually considered a stiff material, steel shapes such as cable, wire rope and rods are highly flexible.

f. Structural Size. The structural size may determine the material of the structure. Large structures such as breakwaters are usually composed of many pieces of one or more materials that may not be bound together to create a homogeneous mass, or composed of sections of the same material

bound together to create a single structure. Small structures such as sand fences may be a series of independent pieces or sections of a material acting in an independent manner.

Structures built of stone, earth and asphalt are generally not capable of resisting tensile stress. They are capable of taking loads in compression, shear and impact only and must be designed accordingly. Concrete and wood may or may not be subjected to tensile stress or bending moments. If concrete is subjected to such stress, reinforcing steel or prestressed cable must be employed to carry the tensile load. Steel is capable of withstanding all types of stress when properly designed. The sections flex or deflect when subjected to bending loads and this movement should be considered in the design phase. Synthetics, particularly the sandbag and filter-cloth materials, are mainly subjected to tension, impacts, flexing, and fatigue. They are seldom required to accept a compressive load.

3. Nonstructural Properties.

a. Durability. Durability is the ability of a material to withstand the effects of service conditions to which it is exposed. Many laboratory tests have been devised for measuring durability of materials but it is extremely difficult to obtain a direct correlation between laboratory tests and field use. Due to the severe coastal environment it is important that field experience be carefully assessed in selecting materials for coastal structures. For a coastal structure to function properly the planned structural life must be known; a structural life projected for a short term (e.g., less than 10 years) may have a major impact on cost and material selection for the structure. The location of the structure with respect to local resources and materials will also impact on the selection of construction materials.

Durability is generally related to the desired lifespan of the structure and the relation between first costs and maintenance. Among the stones, igneous rock is usually the most durable rock. Depending on makeup, it may be extremely durable or, after a few years, may fracture and partially disintegrate. Sedimentary rock should be examined very carefully as it is usually stratified, may not be well consolidated, and is subject to failure through shear stress, impact, fracture due to changes of water content, or chemical deterioration.

Earth is generally considered durable unless changes in water content or chemistry reduce grain size to the silt and clay range, resulting in plastic flow.

Concrete is considered durable and will generally last the planned life of the structure so long as it is not exposed to adverse chemical reaction or excessive abrasion.

Asphalt is generally not considered a durable material. It is of low strength in compression or tension, subject to chemical reactions, and not resistant to impact or abrasion.

Steel is considered durable if properly maintained. However, it is subject to rapid deterioration through corrosion and abrasion. Abrasion

can be severe at the sandline, particularly in a wet-dry tidal area, where steel may deteriorate rapidly.

Wood is considered less durable than concrete but its lifespan depends to a great extent on the characteristics of the wood, the usage, and the quality of maintenance. It is an organic material and subject to attack by both plants and animals. It is more subject to damage by fire than other materials.

Synthetic materials are generally quite durable to chemical attack; however, many will rapidly deteriorate when exposed to sunlight. They require very little maintenance but with most synthetics, because of their short history, their service life relative to the life of the structure is yet to be determined.

b. Adaptability. For any given coastal structure there is usually more than one material or a combination of compatible materials that can satisfy the performance requirements of the structure. Selecting the proper materials as well as design adaptable to the structure site is important. The size of a structure and the accessibility of construction materials to the site must also be considered.

Stone and earth structures can assume a wide variety of shapes. The materials are generally available and, forming nonrigid structures, can for example accomodate changes in foundation elevations or slope adjustments without losing structural integrity or ability to perform their function in the structure. Stone can be used under most weather conditions and will accept major and rapid changes in temperature and moisture without major failures.

Concrete is very adaptable, with or without steel reinforcement. Its use is similar to stone except for the ability to resist abrasion and the cost. Concrete can compete with steel or wood as piles or as sheet pile both in strength and durability.

Use of steel, because of costs, is generally limited to piles, sheet pile. and beams but is extremely adaptable for use in complex structures.

Wood is very adaptable except for limitations on the ability to function well against large wave forces or in greater than moderate depths of water. It resists impact and abrasion well, can resist tension, compression or shear, and is easily handled in construction.

Synthetic and protective coating materials are usually special use items and are not considered as having a wide range of uses.

c. Fire Resistance. Stone and earth are generally regarded as very fire resistant, especially those that are from igneous or metamorphic sources. Sedimentary stone, because of stratification, is less fire resistant.

Concrete is generally fire resistant unless exposed to very high temperatures. Reinforced concrete when exposed to extreme temperatures for

an extended period of time may fail due to excessive expansion of the steel, resulting in spalling and cracking of the concrete.

Steel, of course, is not combustible but if exposed to high temperatures will tend to warp and lose strength. A rigid steel structure may also tend to warp and buckle due to excessive expansion of its members.

Asphalt is vulnerable to relatively low fire-induced temperature rises and is not considered fire resistant. Wood, the least fire resistant of coastal construction materials, is vulnerable to fire.

Synthetics are also vulnerable to fire and may generate dangerous toxic fumes.

4. Availability.

The availability of both the construction materials and the construction equipment necessary to build the structure may limit the selection of materials; e.g.,, a lack of availability of the ingredients required for mixing concrete onsite might necessitate use of more readily available wood or the availability of utilities during construction might limit emplacement methods and thus limit materials used. Site access with respect to local resources and materials must also be considered. For example, in remote areas bringing in steel and concrete may be difficult, while timber is readily available. In this instance, all the properties of wood and its durability must be carefully considered to determine if it is a suitable substitute. This is one of the most important factors influencing the selection, especially when considered in conjunction with transportation costs.

a. Abundance.

(1) Stone. Stone is generally abundant in the continental United States and most outlying areas. However, along the coasts of the Gulf of Mexico and the South Atlantic, sources are 240 kilometers (150 miles) or more from projects so handling costs can become a major factor. In many areas, particularly the volcanic areas of the Pacific Ocean, the stone may be of low density or will be so badly fractured as to not be suitable for armor stone. The mere presence of large stone sources does not guarantee suitability or availability of the stone. Only for a very large project is it feasible to develop a new quarry from virgin rock. Even when a quarry exists, it may not be equipped to produce the type and size stone needed for a particular coastal project. Availability of handling equipment at the quarry may be a critical factor. The cost of quarrying and transporting will affect the choice of stone as compared to some other construction material.

(2) Earth. In most parts of the world an adequate quantity of earth material is available for fills, dikes, and beaches, with two exceptions: in some delta areas, the immediately adjacent earths may be predominantly silts and clays; in some rocky coast areas, beach sands may not be available.

(3) Concrete. The cement, sand, and stone required to make concrete are available in all parts of the United States. Some of the smaller Pacific Islands may require the importation of cement.

(4) Wood. Wood used to be one of the most available construction materials in the United States. It is generally produced within reasonable shipping range of a coastal project. Now, certain types and sizes of hardwoods are becoming more difficult to obtain. In cases where the designer would almost automatically select wood, he now has to compare wood to the relative costs and advantages of other construction materials.

(5) Asphalt. Asphalt is generally available in the United States but may not be available for projects in other areas due to either lack of the material or lack of handling equipment.

(6) Synthetics. Synthetics are a manufactured material, and the location of the plants may not be near the construction site. However, they are easily and economically shipped. There may be a timing problem as some lead time, particularly for large orders, may be required for delivery.

b. Transportability.

(1) Transport Mode. Most construction materials for coastal projects can be transported by conventional freight haulers, i.e., rail, truck, barge, or ship. Armor stone for breakwaters and jetties may have transport problems due to their large dimensions and extreme weight. The design size of armor stone is frequently from 89 to 267 kilonewtons (10 to 30 tons) per stone. Most State highway departments have a load limit of 178 to 214 kilonewtons (20 to 24 tons) per truck. This is not a problem with rail or barge haul but most coastal projects require some use of public highways. This load limitation not only limits the design size of the armor rock, but also requires careful load scheduling to maximize the use of either trucks or railway cars.

(2) Handling Limitations. Coastal projects in isolated locations must be carefully analyzed so that materials selected are capable of being handled by available equipment. This not only involves placement equipment, but transport and processing equipment.

(a) Stone. The primary problem with stone is the handling of armor stone. Quarry processing and loading equipment usually has greater capability to handle large armor stone than public highways will permit. The placement of armor stone on breakwaters and jetties not only requires a certain tonnage lift capability, but the equipment must be able to reach outward a sufficient distance to accurately place the toe rock.

(b) Earth. Earth can generally be handled with conventional construction equipment. The availability of compaction equipment may control the method by which an earthfill is compacted.

(c) Concrete. Many special designs of concrete structures may require highly specialized handling equipment. The costs or availability of such equipment may influence the selection of a concrete structure. Underwater placement, the shaping of concrete armor units such as tribars and

dolos, and the fabrication of reinforced or prestress concrete piles all require specially designed handling equipment. This equipment may or may not have a reuse capability.

(d) Steel. Most conventional steel shaped units can be handled by conventional construction equipment. However, specially designed units, very heavy units, or some types of underwater placement may require handling equipment specifically designed for that particular job.

(e) Wood. Conventional construction equipment can usually transport and handle wood members. However, some types of chemical treatment may require special equipment to effectively penetrate the cells.

(f) Asphalt. For transport and use of asphalt, special heating or hot asphalt handling equipment may be required. If asphalt is placed under water, specially designed handling equipment will be required.

(g) Synthetics. Special handling equipment may be required for placement of synthetic materials, particularly for underwater placement; however, great weights are not usually involved and the equipment can usually be made or adapted in the field.

5. Compatibility With Other Materials.

Problems in compatibility may be physical, chemical, or a matter of esthetics. For composite structures composed of more that one material, such as reinforced concrete, the compatibility of the constituent materials' properties must be considered. Steel of high tensile strength and concrete of high compressive strength used properly together result in a substantially improved structure, while asphalt with high adhesive properties to aggregate can create high wear resistance and a cohesive structure.

Materials may not be compatible due to abrasion effects, particularly between different materials, or even between the same materials (i.e., two stones of different hardnessess may not be compatible in the same structure). Combining flexible with nonflexible structural units may lead to incompatibility. Materials with major differences in shrink-swell or expansion-contraction coefficients may induce physical stress. The weight of heavy structural units on a fragile substructure may cause failure. All these are generally stress, fatigue, or abrasion problems.

Chemical incompatibility is particularly critical in the choice of cement and aggregates, selection of synthetics, use of asphalt, electrolysis or corrosion of steel members, and corrosive interaction of dissimilar metals. The effect of incompatibility of materials may take a long time to appear and, if chemical action is allowed to continue, can result in structural failure.

Compatibility of traditional methods or materials with new and sometimes untried construction techniques with a short experience record, must be carefully considered.

6. Maintenance and Preservation Requirements.

These requirements and their annual costs are generally influenced by comparison with the initial costs of construction. All materials require some maintenance and preservation. The problem may be physical or chemical maintenance and may vary not only between different materials but within the same material.

a. Stone. It is unusual, but possible, that stone will deteriorate chemically. The main problems are reduction in size through abrasion, reduction in size through splitting or breaking, particularly of armor stone, and loss of stone due to the power of waves or currents, or the undermining of the structure. Preservation of stone as a material is not generally feasible and maintenance is normally a matter of replacing damaged or missing stones. Generally, damage to a breakwater, jetty, or groin does not cause severe resultant damage immediately but mobilization costs to do maintenance work are high.

b. Earth. Little can be done to preserve an earth structure except to protect it from erosion. Like stone, maintenance is a matter of replacing lost material. Ease of access to the earth part of an installation will determine the maintenance cost.

c. Concrete. The quality and the life of concrete are largely controlled by the methods of mixing and placing. Coatings are available which improve the set period of the concrete and protect the surface from flaking or dusting. In saltwater, and to a lesser extent freshwater, if the reinforcing steel is exposed to oxygen it will combine to produce corrosion. The corroded surface of the steel expands greatly, resulting in cracks in the concrete that admit more water and accelerate the process. The result is physical spalling, cracking, or splitting of the concrete resulting in total failure. Such cracks must be kept sealed to slow this process. As cement has a calcium base, it may be necessary to protect it from chemical change by pollutants or biological attack. Like stone, the primary need for maintenance or preservation is to prevent deterioration. This may be from abrasion by harder and sharper substances, such as quartz sands, or from the force of storm waves overstressing the structure. Impact by rocks, barges, ships or debris may overload concrete, as in the case of dock structures. Seismic damage may occur. Maintenance may consist of sealing cracks, patching abraded or worn areas before the reinforcing steel is exposed, or actually replacing individual concrete units within the structure.

d. Steel. In contrast to stone and concrete, the primary purpose of maintenance or preservation of steel structures is to prevent chemical or galvanic deterioration. Unless made of special and expensive alloys, exposed steel is subject to rapid deterioration through oxidation or rust, especially in the wet-dry tidal area and at the sandline. The latter can be very severe in the surf zone where the corrosive process is accelerated by the abrasive action of the sand continually removing the rust and exposing new steel. The application of paint or some of the new protective coatings can greatly increase the life of such steel members. The galvanic process can be greatly reduced or eliminated by the installation and maintenance of "cathodic protection systems."

Physical failure will not normally occur from wave or current forces if steel structures are properly designed. Primary cause of failure will be severe damage by ships, barges or debris, or in the case of a dock, through overloading. Prompt replacement of buckled members is mandatory to prevent further damage to adjacent members.

e. Wood. The greatest cause of deterioration of wooden structures is biological attack. This may be by plant or animal life and may occur completely above or below the waterline but is most likely to occur in the wet dry tidal area. Most of these species require some sunlight but there are some that are active in total darkness. Only below the mud line are wood members safe from such attack. Two methods of preventive maintenance are available--complete impregnation of the cells of the wood by chemicals, or the application of a surface coating that prevents entry of borers into the timber. Surface coatings may be coatings such as antifouling paint or a coating material resistant to borer penetration, such as a thick, 0.5-millimeter (0.020 inch), epoxy coating, a synthetic film wrapped around the wood members or a membrane of concrete (usually about 50 millimeters thick) completely surrounding the wood members. Without such protection, a wood structure will deteriorate rapidly making a sustained maintenance program of inspection and prompt replacement necessary to a long service life of the structure.

Physical damage generally consists of broken members due to damage by ships, barges, or debris, or by the force of storm waves. Prompt replacement of broken members is necessary to avoid deterioration of adjacent members. Damage through chemical reaction is largely confined to unusual events in industrial harbor basins. A side benefit of pollution of harbor waters from industrial activity may be the almost complete absence of marine life that attack wooden structures.

f. Asphalt. This is primarily used as a surfacing material for harbor roads, parking areas, and storage zones. It is subject to chemical deterioration, abrasion, plastic flow under heavy loads, and vehicular impact, particularly in areas subjected to high temperatures. Continuous maintenance is required or damage will not only be extensive to the asphalt structure, but also to vehicles and equipment using it. Where asphalt is used on jetties, frequent inspection and replacement of broken or dislodged asphalt is required.

7. Environmental Considerations.

The physical properties and performance experience of each of the coastal structural materials are discussed in detail in the following sections. The environmental impacts considered on each of the materials are: corrosive and pollutant attacks on exposed surfaces, the effects of sunlight, water penetration, waves and currents, severe temperature, ice, marine organisms, periodic wetting and drying, wind erosion, burrowing animals, flora, fire, abrasion, seismic effects and human activity. While all of the above impacts do not effect all structural materials (for example, fire does not change the physical properties of earth), those environmental impacts that may effect a specific structural material to be considered for use in coastal construction are discussed in the appropriate material section.

III. STONE

1. Types and General Characteristics of Stone.

a. General. "Stone" refers to individual blocks, masses, or fragments that have been broken or quarried from bedrock exposures, or obtained from boulders and cobbles in alluvium, and that are intended for commercial use. Stone is used for many purposes, which are generally divided into two main classes: (1) "Physical" uses, in which the stone is broken, crushed, pulverized, shaped, or polished, but its physical and chemical characteristics remain essentially unchanged; (2) "chemical" uses, in which the stone is changed physically or chemically to yield an end product that differs from the raw stone in composition. The use in coastal structures is primarily of a physical nature.

Crushed and broken stone includes all stone in which the shape is not specified, such as that used as aggregate and riprap. Riprap is well-graded within wide size limits. Quarrystone armor consists of comparatively large broken stone that is typically a specified size and is used, without a binder, principally for breakwaters, jetties, groins, and revetments, which are intended primarily to resist the physical action of water.

Stone for coastal structures should be sound, durable, and hard. It should be free from laminations and weak cleavages, and should be of such character that it will not disintegrate from the action of air, seawater, and undesirable weathering, or from handling and placing. In general, stone with a high specific gravity should be used to decrease the volume of material required in the structure and to increase the resistance to movement by the action of waves or currents.

Characteristics that affect the durability of stone are texture, structure, mineral composition, hardness, toughness, and resistance to disintegration on exposure to wetting and drying and to freezing and thawing. Ordinarily, the most durable stone is one that is dense or fine textured, hard, and tough, but exceptions to this general rule occur. The character of the stone for any project depends on what is available, and often the choice of material involves weighing the relative economy of using a local stone of lower quality against using a better quality stone from a distance. Where the local stone is markedly inferior, the greater cost of transporting durable, high-quality stone from outside the immediate area may be justified and advisable. Because of the wide range in climatic conditions and, thus, of the serverity of exposure in different regions of the United States, acceptable standards of durability for these various regions will vary.

The stone industry recognizes the following stone classification (Gay, 1957) based mainly on composition and texture: (1) granite; (2) basalt and related rocks; (3) limestone and marble; (4) sandstone; and (5) miscellaneous stone (including chert, conglomerate, greenstone, serpentine, shale, slate, mica schist, tuffaceous volcanic rocks, and coral).

b. Granite. The term "granite" is commonly applied to medium- to coarse-grained igneous stones that consist mainly of feldspar and quartz, and ordinarily contain subordinate proportions of ferromagnesian minerals. Mica may also be present. In small quantities mica is not particularly

harmful; however, in larger quantities it sets up planes of structural weakness and provides a starting point for disintegration. Granite occurs mainly in large bodies, known as batholiths, which are exposed over many square miles. Batholiths commonly consist of numerous individual bodies of various granitic rock types, with contrasting colors, textures, and mineral composition.

While granites vary widely in texture and appearance, most of them are dense and have a porosity of less than 1 percent. Granite spalls badly under the combined effect of fire and water, so it is not particularly resistant to fire. Most unweathered granitic stones are hard, strong, tough, and resistant to abrasion, impact, and chemical attack. The average unit weights range from approximately 24.3 to 27.5 kilonewtons per cubic meter (155 to 175 pounds per cubic foot). These properties make granitic stones well suited to use as riprap and quarrystone armor units.

c. Basalt and Related Stone. In commercial usage, the term "basalt" is applied to any of the dense, fine-grained, dark-gray or black volcanic stone. The term ordinarily includes stone types that geologists classify as dacite, andesite, basalt, trachyte, or latite. Basaltic rock has solidified by the cooling of lava, either as flows on the Earth's surface, or as shallow intrusive bodies beneath the surface. It is composed primarily of feldspar and ferromagnesian minerals in crystals that range in size from submicroscopic to clearly visible. Commonly, an appreciable percentage of glassy material is present. Some effusive basalt is vesicular and the vesicles may have become filled with potentially reactive substances such as opaline, silica or zeolites which render the rock unfit for use as aggregate.

Basalts are one of the heaviest stones with an average specific gravity of 2.9 to 3.2 and average unit weights of 28.3 to 31.4 kilonewtons per cubic meter (180 to 200 pounds per cubic foot)); however, in certain areas they may contain many small cavities (vesicles) which result in stone with low densitities. Basaltic stones are characteristically hard, tough, and durable, so they are well suited for use as aggregate, riprap and quarry-stone armor units.

d. Carbonate Stone. Carbonate stones are broadly divided by geologists into (1) limestone, which consists almost entirely of calcite ($CaCO_3$); (2) dolomite, which consists mainly of the mineral dolomite ($CaCO_3 \cdot MgCO_3$); and (3) marble, which is the metamorphosed crystalline equivalent of either type. All gradations exist between limestone and dolomite and between very fine-grained and very coarse-grained material.

In the stone industry the term limestone is applied to many types of rock that contain a high percentage of calcium carbonate, although large proportions of other substances also may be present. Such substances include siderite ($FeCO_3$), magnesite ($MgCO_3$), and rhodochrosite ($MnCO_3$). They also commonly contain clay, silt, and sand grains. A high percentage of clay commonly weakens carbonate rock, making it unfit for use as stone. A high content of sand grains or silica may harden carbonate rock. Marble is similar to limestone chemically, but has been subjected to a metamorphic process which has made it more crystalline in structure, harder, and better able to hold a polish.

For use as stone, carbonate rock should be physically sound, dense, and relatively pure. Porosity of limestone generally ranges from approximately 1 to 15 percent. Limestones have an average unit weight of approximately 22.0 to 25.9 kilonewtons per cubic meter (140 to 165 pounds per cubic foot). Marble has an average unit weight of 25.1 to 26.7 kilonewtons per cubic meter (160 to 170 pounds per cubic foot). Carbonate stone that is tough, strong, and durable is well suited for use as concrete aggregate, riprap and quarrystone armor units.

e. Sandstone. Sandstone is clastic sedimentary rock composed of particles mainly in the size range of about 0.25 to 6.4 millimeters (0.01 to 0.25 inch) in diameter. Although some sandstones consist almost wholly of quartz grains, most sandstones are feldspathic; some contain a high proportion of ferromagnesian minerals. The strength and durability of sandstone are mainly determined by the type of material that cements the grains together. Only well-indurated sandstone, cemented with silica or calcite (rather than with the weaker cements, clay or iron oxide), is well suited to use as crushed and broken stone. The porosity of sandstone is typically high, ranging from 5 to 25 percent. The average unit weight ranges from approximately 21.2 to 25.1 kilonewtons per cubic meter (135 to 160 pounds per cubic feet).

f. Miscellaneous Types of Stone.

(1) Chert. Chert is a sedimentary rock composed almost entirely of silica, in the form of opal, chalcedony, or microgranular quartz. It commonly occurs in thin-bedded deposits. The most desirable form of chert is hard and dense, which is well suited for use as crushed and broken stone and riprap. Some chert, however, is too laminated or contains too much silt or shale for such use. It is generally not used for large quarrystone armor units.

(2) Conglomerate. This stone is clastic sedimentary rock containing abundant fragments of pebble size or larger in a matrix of sand and finer grained materials. Conglomerates show various degrees of induration which depend largely on the nature and amount of cementing material--clay, calcium carbonate, iron oxides or silica--in the matrix.

Conglomerate is not abundantly used for riprap or quarrystone armor because relatively few deposits of conglomerate are sufficiently well indurated for this use.

(3) Greenstone. Greenstone is a general term applied by geologists to basic or intermediate volcanic rocks that contain abundant green secondary minerals. In the stone industry the term is also applied to a variety of fine-grained green rocks, including arkosic sandstone, graywacke, impure quartzite and various pyroclastic rocks. Physically sound greenstone may be used for aggregate, riprap, or quarrystone armor, if it is available economically.

(4) Serpentine. This stone is an ultrabasic igneous rock composed mainly of the mineral serpentine, a hydrous magnesium silicate. Serpentine rock is moderately soft, but commonly massive and dense in structure, and

very resistant to chemical and physical weathering. These properties make it desirable as crushed and broken stone for riprap, but generally not for quarrystone armor units.

(5) Shale. Shale is a very fine-grained, thinly bedded sedimentary rock composed mostly of clay-size and silt-size particles. Pre-Mesozoic shales are commonly well indurated, if not metamorphosed. Most Mesozoic and Tertiary shales are moderately to poorly indurated. Most types of shale are too weak to be suited to the ordinary uses of crushed and broken stone.

(6) Slate. This stone is a thinly foliated metamorphic rock composed essentially of muscovite (sericite), quartz, and graphite, all in grains of microscopic or submicroscopic size. Slate is formed by compaction and partial recrystallization of shale, and is commonly dark colored and moderately hard. Slate is desired mainly for use as dimension stone. Because slate has been subjected to intense pressure during formation, it has a low porosity and, consequently, a high strength. Its modulus of rupture is relatively high, and it is also resistant to weathering and to mechanical abrasion. The average unit weight ranges from approximately 26.7 to 28.3 kilonewtons per cubic meter (170 to 180 pounds per cubic foot).

(7) Tuff. The term "tuff" includes pyroclastic volcanic types, most of which would be classed as rhyolite or dacite tuffs or tuffaceous sediments. Most tuffaceous rocks are only moderately hard, although on exposure to air they commonly harden appreciably. Because of its softness, tuffaceous rock is unsuited to most uses of crushed and broken stone.

(8) Coral. In southeastern United States and certain Pacific Island areas, it is often necessary to make use of coralline limestones for coastal construction, since more durable stone (such as granite or basalt) is unavailable. These materials are partially recrystallized coral formations which have sufficient resistance to breakdown and erosion to be acceptable for breakwater or revetment construction (Fig. 1). They are less resistant to mechanical breakage than denser, harder stone and therefore, require special care in blasting and handling. However, it has been possible to produce large stones 89 to 267 kilonewtons (10 to 30 short tons) from coralline limestones.

2. Categories of Stone Size and Gradation.

a. General. The category of crushed and broken stone includes all quarried stone that is not cut or shaped to specified dimensions. It ranges in size from granite blocks weighing 222 to 267 kilonewtons (25 to 30 short tons) used as quarrystone armor units, to ground shale of very small size to smaller than 200 mesh (0.075 millimeter) used as insecticide carrier. The larger categories of crushed or broken stone (greater than 75 millimeters or 3 inches) are generally used in coastal construction.

b. Fill. Most fill material is natural earth obtained as surplus from excavation or from borrow pits, and would not be classed as stone. Crushed stone is used for special types of fill, such as the cores of dikes or jetties. Only the least expensive grades of crushed stone, commonly

Figure 1. Coral riprap in Kosrae, Micronesia (photo courtesy of Woodward-Clyde Consultants).

crusher run fines or unclassified waste from production of riprap, are used for fill. Miscellaneous soil, rock and rubble fills may be used as random or temporary shore protection (Fig. 2).

c. Rockfill. Sound rock is ideal for producing rockfill materials. Some weathered or weak rocks, including sandstones and cemented shales (but not clay shales), may also be suitable (U.S. Army, Corps of Engineers, 1971b). Rocks or stones that break down to fine sizes during blasting, excavation, placement, or compaction are unsuitable as rockfill; such materials should be treated as soils. Processing by passing rockfill materials over a grizzly may be required to remove excess fine sizes or oversize material. Quarry-run and quarry-waste materials are commonly used as core materials for breakwaters and jetties. This material should be reasonably well graded and no skip grading or scalping of certain sizes should be allowed. The material should also generally contain no more than 5 to 10 percent fines.

d. Riprap. Riprap is generally heavy irregular fragments of broken stone or other resistant substances, well-graded within wide size limits, and randomly placed without mortar to provide protection for an embankment or bluff toe from the physical erosive action of water. The stability of the stone layer depends on the density and mass of the stones, and on the evenness of their gradation. The stability increases as the stones become more well graded. This means that, for riprap of small stones, finer material is included in the gradation, making voids smaller, the face smoother, and wave reflectance higher. As long as the physical requirements for stone are fulfilled, any type of rock may be used for riprap; chemical and mineral composition of the rock is generally of minor importance.

Figure 2. Random miscellaneous dumped soil, rock and rubble fill used as shore protection, Sunset Cliffs, San Diego, California (photo courtesy of the City of San Diego).

e. Armor Stone. Armor stone, chosen to be of nearly uniform size and of compact, sometimes blocky shape, depends on density and mass to resist the force of waves or currents. The voids between the armor rock, to a certain extent, absorb energy through creation of turbulence. To a lesser extent, wave energy is absorbed by wave runup on the sloping outer face.

f. Underlayers. The underlying rock layers are usually randomly placed and serve to support the armor rock. By size gradation, and sometimes in several layers or zones, they may also absorb wave or current energy through turbulence in the voids. Rocks used for these underlayers are considerably less costly per unit volume than armor rock.

g. Bedding Layers. In breakwaters, jetties, and groins constructed on relatively flat sand or mud bottoms, a bedding layer consisting of smaller well-graded stones is required to prevent the fine bottom material from piping upward through the structures. Piping and subsequent erosion of the foundation soils could result in settlement of the upper layers of rock, particularly the large heavy armor stones. Settlement could in turn cause ultimate collapse of that part of the structure.

h. Filter Layers. In revetments, seawalls, and bulkheads a layer of filter material is required. While this layer of fine well-graded stones may in part act as a supporting bedding layer for sloped revetment or seawall structures, its primary function is to relieve hydrostatic pressures due to changes in water elevation on the seaward side or changes of ground water elevation on the landward side. It is designed as a true filter to permit the passage of water in either direction, but to prevent the disturbance of the sand or clay foundation. The gradation of the filter material depends on the characteristics of the backfill core or beach materials and on the voids of the riprap or armor units. The filter material should be uniformly graded from fine sands, coarse sands, gravels and stones such that it will not wash into the rubble. The material could be in two or more layers. It should also be noted that filter cloth is frequently used in place of a graded granular filter.

i. Other Categories. Filler stone, consisting of well-graded gravel size material, 6.3 to 100 millimeters (0.25 to 4 inches), is commonly used to fill the voids in core stone. Toe stone is used to protect the base of a coastal structure from erosion or scour. This stone typically ranges from approximately 0.89 kilonewton (200 pounds) to more than 8.9 kilonewtons (2 000 pounds) in weight and should be reasonably well graded. Chink stone is used to fill voids in riprap or armor stone. Coarse and fine aggregates are used for making concrete.

j. Fill for Gabions and Cribs. Gabions are wire baskets that can be connected and filled with stone. The baskets must be solidly filled, or wires will be abraded by movement of loose stones. The stones must be large enough, generally 10 to 25 centimeters in diameter, to prevent loss of stone through the gabion mesh. Cribs may be filled with similar stone materials to form a gravity type structure.

5. Stone Specifications.

a. General. The character of the stone to be used in coastal structures is of primary importance. Materials may be obtained from any approved

local source. Material from new sources should be tested by the Government for quality to determine acceptability. When the contractor desires materials from a source not listed, or if the Government elects to retest a source that is listed, suitable samples for quality evaluation should be taken by the contractor under the supervision of the contracting officer. Samples are generally delivered by the contractor to the nearest Corps of Engineers laboratory for testing.

No standard testing procedures have yet been developed for the determination of the quality of stone. The Waterways Experiment Station (WES) and some Corps Division laboratories have devised tests to evaluate such material, but the test procedures employed in these different laboratories vary somewhat. In any case, judgment is necessary in applying the test results. Any testing program for the determination of the quality of rock for use as stone in coastal structures should include petrographic examination: determination of absorption and bulk and specific gravity {ASTM Standard C97-47 (77) or C127-77}; a soundness test {American Association of State Highway and Transportation Officials (AASHTO) Test T-104-46 or ASTM Standard C88-76}; and an abrasion test {ASTM Standard 535-69 (75)}. Other tests that may also prove useful include a slaking or wetting-and-drying test, and a freeze-thaw test. See Lutton, Houston, and Warriner (1981) for details.

Properties contributing to durability of stone may be both physical and chemical. Tests usually measure physical properties and therefore the results provide only an indication of how chemical change has already affected the stone, not the susceptibility to future chemical change. Wetting and drying tests have been used to evaluate rock which disintegrates badly as a result of chemical change, but there is still a question as to what the test actually measures and what the results mean. Chemical changes can best be evaluated by experience.

The best data for evaluating stone to be used in coastal structures are service records. If a stone has not been previously used, the quarry should be visited and old surface outcroppings examined for signs of weathering.

b. Stone Size. To make optimum use of local materials, designs should not only have a wide range of stone sizes to choose from, but also an adequate number of classes within this range. Each class available for a specific use should be limited in range. Physical limitations in the size of armor stone that is feasible to use must also be considered. These may be truck or highway capacity or the handling limits of the quarry equipment. The geological structure of the rock quarry may also limit the quantity and size of stone that can be obtained.

The total weight or size of the armor units, the side slopes, the density of armor material, and the degree of interlocking or wedging between units are interrelated and comprise the principal factors in the design of a stone structure. Armor stone may be rubble mound placed at random, individually placed, or it may be rectangular blocks of stone carefully fitted together. Several empirical formulas have been derived for determining the size of armor stone required for the stability under wave action. These are contained in the appropriate design manuals. In the Hudson equation for design of armor stone {U.S. Army, Corps of Engineers, Coastal Engineering Research Center (CERC) 1977}, the required size of

individual armor stone is roughly inversely proportional to its density. This flexibility of size versus density of stone permits some latitude in choice between two quarry sites. Stones larger than about 223 to 267 kilonewtons (26.1 to 30.0 short tons) are generally not easily handled. The greatest dimension of each individual large stone should be no greater than three times the least dimension.

The reverse of this size-density factor can be used for a more efficient consideration of choice of rock source for core and underlayers where density is not a critical design consideration. Frequently a savings in cost can be affected by bidding the armor stone in tons and the underlying stone in solid cubic yards. Underlayers placed beneath the armor units should be an adequate size to prevent withdrawal of the units through the interstices of the cover layer and to prevent excess movement and subsequent breakage. The weight of underlayer stone may range from 3 to more than 30 kilonewtons.

The most frequently used core is of a quarry-run material, the gradation of which is governed by economics or by the desired degree of impermeability. A rubble structure may also need protection from settlement (resulting from leaching, piping, undermining, or scour) by use of a bedding layer or blanket. The gradation requirements of a bedding layer depend primarily on the littoral chracteristics in the area and on the foundation conditions. However, quarry spoil, ranging in size from about 4 newtons (1 pound) to about 220 newtons (50 pounds), will generally suffice.

Typical classifications from the State of California Standard Specifications for rock slope protection are shown in Table 1 (California Department of Public Works, 1960). The weights by which the classes are designated do not necessarily correspond to the weights called for by the various design formulas. For example, if a shore protection formula, such as Hudson's equation in the Shore Protection Manual (SPM) (U.S. Army, Corps of Engineers, CERC, 1977), should call for 5-ton (44 kilonewton) armor stone, it may be proper to use the 8-ton (71 kilonewton) class, as approximately 80 percent of this class would be larger than 5 ton. For the same example, the SPM suggests that for a cover layer with a two stone thickness, approximately 75 percent of the stones may be greater than 5 tons and the range should be between approximately 3.75 and 6.25 tons (33.3 and 55.6 kilonewtons).

c. Stone Shape. Stone block structures may be closely fitted seawalls, groins, jetties, or breakwaters such as are built along the coasts of Hawaii (Fig. 3), the Gulf of Mexico, and the Great Lakes. For these structures the stone blocks should be rectangular and of sufficient uniformity in size and shape to be closely fitted together. These structures depend on the close fitting of the armor stone and chinking or grouting to prevent loss of the underlying rubble stone through the interstices of the fitted armor stones. However, there must be sufficient space or openings between the armor stones to relieve the hydrostatic uplift pressures that occur during storm waves.

Rounded stones, particulary for the armor layers, are to be avoided whenever possible. They are difficult to place and are not stable, either due to wave forces or their inherent instability on steep slopes. For these reasons, field or streambed stone are generally not acceptable.

Table 1. Classes of rock slope protection (from California Department of Public Works, 1960).

Rock sizes	Placement Classes											
	Method A[1]					Method B[2]					Backing	
	8 ton	4 ton	2 ton	1 ton	1/2 ton	1 ton	1/2 ton	1/4 ton	Light	Facing	No. 1	No. 2
8 ton	50	0										
4 ton	95	50	0									
2 ton	--	95	50	0		0						
1 ton	--	--	95	50	0	50	0					
1/2 ton	--	--	--	95	50	--	50	0				
1/4 ton	--	--	--	--	95	90	--	50	0			
200 lb	--	--	--	--	--	--	90	--	50	0		
75 lb	--	--	--	--	--	--	--	90	--	50		
5 lb	--	--	--	--	--	--	--	--	90	90	0	
No. 4	--	--	--	--	--	--	--	--	--	--	50	0
No. 200	--	--	--	--	--	--	--	--	--	--	95	90

[1] Method A. A footing trench shall be excavated along the toe of slope. The larger rocks shall be placed in this toe trench. Rocks shall be placed with their longitudinal axis normal to the alignment of the embankment face, with attitute horizontal or dipped slightly inward, and arranged so that each rock above the foundation course has a 3-point bearing on the underlying rocks. Bearing on smaller rocks which may be used for chinking voids will not be acceptable. Placing of rocks by dumping will not be permitted. Local surface irregularities of the slope protection shall not vary from the planned slope by more than one foot measured at right angles to the slope.

[2] Method B. A footing trench shall be excavated along the toe of the slope. Rocks shall be so placed as to provide a minimum of voids and the larger rocks shall be placed in the foundation course and on the outside surface of the slope protection. The rock may be placed by dumping and may be spread in layers by bulldozers or other similar equipment. Local surface irregularities of the slope protection shall not vary from the planned slopes by more than one foot measured at right angles to the slope.

Figure 3. Fitted stone blocks in Hawaii.

Angular stones (Fig. 4), particularly for the armor layer, have two advantages: (1) the voids are maximized, increasing energy losses through turbulence; and (2) the stones tend to interlock with their neighbors, increasing their resistance to movement by wave or current forces.

Figure 4. Angular block stones.

While angularity is most desirable, the stones should be approximately rectangular in shape. For large stone, the greatest dimension should be no greater than three times the least dimension. Sharp points should be avoided as they may cause a stone to wobble or the point may break off under stress, disturbing the stability of the section. Even if dislodged or partially dislodged, an angular stone will tend to find a stable position, whereas a rounded stone will tend to roll to the toe of the structure.

d. Specific Gravity. Required stone size is a function of the specific gravity and, unless unreasonably low, specific gravity should not be a limitation on its use. In fact, excellent results have been reported for lava with a specific gravity of 1.5. Once the stone size has been selected on the basis of a certain specific gravity, specifications should then prohibit the use of stones with specific gravity appreciably lower. Low density stone may be used in the core (and underlayers), and high density armor stone can be used, providing an adjustment is made in the thickness, for the armor layer. Armor is generally priced by the ton. Core and underlayer materials may be priced by volume to control the use of overweight stone in these zones.

e. Absorption. There is a general correlation between absorption and weathering. Use of the absorption test is more significant when the rock is to be used in areas subject to freezing and thawing. A limit of 2-percent absorption is reasonable.

f. Soundness. Rocks that are laminated, fractured, porous, or otherwise physically weak are subjected to a soundness test (use of sodium sulphate). Stones showing a loss of less than 5 percent should be satisfactory.

g. Abrasion. The Los Angeles rattler test and Wetshot rattler test measure resistance to abrasion. Use of these tests is more significant when the rock is to be used in shore protection where it is subjected to a pounding surf carrying sand, gravel, and smaller stones. Stones having relatively high losses in these tests have performed satisfactorily in shore protection and therefore a rather lenient value is permissible. A 40-percent maximum loss for the Wetshot rattler and 45 percent for the Los Angeles rattler are considered reasonable.

4. Quarrying Methods.

a. Quarry Development. Quarries produce most of the rock required for construction in this country. In most quarries, all the material mined is usually consumed as an end product. The size and quality of material obtained from a quarry depend largely on the geology of the site and the method of blasting (duPont de Nemours and Lo, 1977). Depending on the area's topography, a quarry will generally be developed either as a side hill or as a pit-type operation. Where the area is hilly and the rock outcrops, the quarry will be developed by opening a face into the side of the hill. The point of entry is usually at the bottom of the rock seam or in a very thick seam. A convenient point should be chosen to provide an almost level floor with just enough slope for natural drainage. When the

terrain is almost flat, it is necessary to ramp down into the rock creating a pit that is entirely below the surface of the surrounding terrain.

The height of the quarry face may be determined by the thickness of the formation. However, since most formations being mined exceed the practical limits of bench heights, the determining factor in the choice of bench heights is usually that of safety. Bench heights must be selected to be compatible with the loading equipment so that the broken rock can be safely removed from the muck pile. If a single piece of loading equipment, such as a shovel or front-end loader, is incapable of reaching high enough to remove all unstable rock from the broken bench face, then it is customary to use a dozer to work the rock down to a safe height for the loader. The use of the proper blast design will result in the utilization of the maximum safe bench heights and the optimum use of loading equipment.

A somewhat special method used in quarry development is called "Coyote Tunneling." This is a method in which tunnels are excavated into a bluff or hillside and partially filled with explosives. In a crude sense, they might be considered large-diameter horizontal boreholes, with the additional option of turning corners or excavating "tee" sections. With this method, it is extremely important that the natural jointing characteristics of the rock have the capability of producing the desired material, since there is relatively limited additional fragmentation by this blasting method itself. The method is economically attractive if there is a vertical or steep rock face and the rock has the desired jointing characteristics. For example, it has proved to be very successful for producing riprap in columnar basalts, and for producing crusher feed in diced basalts.

Dimension stone quarries may be developed in some formations such as sandstone, marble, or granite. Drill holes are generally spaced close together along the desired break line and small charges of blasting powder are used in these quarries. The purpose is to move a block of stone a short distance in one piece without any damaging cracks.

b. Blast Design. In general, the blasting method is determined by the geology of the material to be broken, the fragmentation required, the hole diameter, and the type of explosive. The type of equipment available for handling and loading should also be taken into consideration (e.g., in determining bench height).

(1) Geology. The geological and physical characteristics of the material to be broken are the most important factors in determining the end-product stone size and the overall blast design. There are at least a half dozen or more factors reported by researchers as being related to the manner in which rock is fragmented under the action of explosives. These include such factors as the maximum sonic velocity, the minimum sonic velocity, the ratio of these two (the sonic anisotropy), the lowest tensile strength, the specific gravity, and the number of joints intersecting a blasting round. Factors such as hardness and brittleness may also be included, but these are related to those previously mentioned. At least a part of these properties are measured or estimated in a typical site investigation for a quarry. Even the most cursory of quarry investigations will provide an estimate of rock quality and jointing. In turn, rock quality and jointing are probably the two most important factors used in preliminary design of blasting

tests. However, it is generally true that both the design of blasting rounds and the chances of their success largely depend on the previous experience and skill of the blaster.

In many cases, a very hard, brittle rock will break with less difficulty than a soft, spongy rock. This is dramatically true if the hard rock is closely jointed and the soft rock is massive. The orientation of the primary joint system in a formation is a very important factor in the blast design. When the primary jointing is dipping at a steep angle, it is usually advantageous to develop the quarry face at no less than 45° (and preferably 90°) to this jointing angle; however, this is not universally true. In determining the angle of the quarry face, consideration should also be given to the desired end product (e.g., crusher feed versus riprap), slope stability questions, ease of development, traffic flow, and equipment. Frequently, the direction of development is not a controllable factor. In such cases, it is important to make certain that blast designs and excavating procedures take into account the geometric relationships between the jointing, explosives action, excavating sequences, and final surfaces.

(2) Fragmentation. The degree of fragmentation desired depends on the end use of the product mined. In quarrying, where the stone will be sized for construction use, it is usually undesirable to produce a large percentage of stone less than 5 centimeters (2 inches) in size. Even under the best conditions, it should be anticipated that up to 5-percent fines (fine sand, silt, and clay) will be generated by the blasting operation.

Because many of the various parameters involved in blast design are strongly interrelated, it is difficult to isolate each factor and discuss its relationship to the final product. However, it is possible to make certain statements which are generally true about some of these parameters. For example, a high powder factor (quantity of explosive per unit volume of rock) will produce a greater degree of fragmentation than a lower powder factor if other factors are kept the same. Similarly, greater fragmentation will be achieved in a massive rock by using a larger number of smaller diameter holes at closer spacing, rather than larger diameter holes at greater spacings. Also, it appears that the best fragmentation is achieved when holes are detonated individually rather than simultaneously.

(3) Hole Diameter. The proper hole diameter depends largely on the physical properties of the formation, the fragmentation required, and the height of the quarry face. The hole diameter should be selected to be compatible with the geological and physical characteristics of the formation, since it is the only factor in the overall blast design that cannot be altered. Unfortunately, this selection is sometimes made on the basis of the total volume of rock to be mined, the duration of the project, production rates, capital costs, and depreciation rates, with no consideration given to geology.

(4) Type of Explosive. On large-scale projects, it can be reasonably assumed that the first choice of explosive will be made for economical rather than technical reasons; for dry quarry work, explosives will usually be ammonium nitrate fuel oil (ANFO). If water is encountered, the choice would normally be a specially packaged ANFO or some form of slurry or water gel. Despite its relatively low price, ANFO is a good, general-purpose

explosive. Its low brisance is compensated for by its high gas volume. Hence, it is capable of producing as much work as some of the more expensive brisant explosives.

The majority of blast-induced fractures produced in the rock are radial from the charge location, and are associated primarily with the propagating stress waves (duPont de Nemours and Lo, 1977). Spalling at the bench face from reflected stress waves produces very little fragmentation with the burdens normally used under typical field conditions. Thus, it is apparent that the inherent fracture planes in the rock are important and should be considered in determining the fragmentation; hence, they should also be considered in determining the blast design. If the inherent fracture planes are closely spaced, the material can be broken more easily and with larger diameter holes at greater spacing.

Production of large stones is usually a more difficult problem than production of crusher feed. If the rock is overblasted, and the particles are too small, there is no way, of course, to make them larger. However, if rock sizes are too large, it is at least physically possible to break them to smaller sizes, although at greater cost. For the production of large stone, it is customary to detonate simultaneously a row of holes behind an open face, using relatively light charges.

c. Loading Equipment. The degree of fragmentation required is also related to the type and size of the loading equipment, and the size and type of crusher available. Obviously, larger equipment can tolerate larger rock fragments. However, the main advantage of larger equipment is its ability to handle a larger volume of material, not simply larger particles. It is poor economy to use larger blast-hole spacings and burdens to produce larger rock sizes because large loading equipment has been acquired. Under these circumstances, the loading and crushing equipment is not being utilized to its maximum capabilities. It is much less expensive to do more work with explosives. Of course, if the needed product is large-size stone, such as riprap, it is essential to have equipment capable of handling it.

d. Processing of Materials. The properties and quantities of the various types of materials are not only dependent on the onsite geological conditions, but also on the construction procedures; therefore, it is imperative that suitable processing methods be used in the quarry operation. Further, it should be anticipated that variations and changes from the anticipated geologic conditions in the quarry may occur and methods of construction may vary.

The large number of material types generally obtained from a quarry require separating materials into various sizes and gradations. Very large material, up to 267 kilonewtons (30 short tons), may require special equipment. It is anticipated that large stone material, e.g., 1- to 8-ton stone, will be separated by the excavating equipment. The material larger than 0.6 meter (24 inches) and smaller than 38 millimeters (1.5 inches) is generally removed and separated by some type of screening process. Removal of fines (material passing a No. 200 mesh sieve) may require some type of washing process. The various operations could have a significant effect on the material gradation and generation of fines which would ultimately affect the available quantity of some of the material types. It is there-

fore important that the sequence of operations, type of equipment, rate of production, and number of times the material is handled be evaluated and controlled.

The best time to control the gradation of quarried stone is during the quarrying. Control of gradation to meet specifications is usually carried out by visual inspection. In order to calibrate the judgment of the inspector, it is very helpful to establish, at a convenient location in the quarry, a pile of stone with the desired gradation. This standard pile should contain 44.5 to 89 kilonewtons (5 to 10 short tons) of material, and should be formed by measuring and selecting the individual stones to be combined in the correct proportion. In the case of riprap, or other large stone, there may need to be a larger volume in the pile used for visual calibration.

Some projects may permit the use of "quarry run"; i.e., whatever quality and gradation of stone that may come from the quarry without any special control or processing. However, when specifications are being prepared, it is very important to the project owner that any limitations be carefully identified. He may expect quarry run to be the product of very cautious blasting using controlled methods and he may encounter either a design problem or contractual problem if entirely different methods are used by the contractor.

It should be anticipated that even fresh rock will contain up to 5-percent fines due to blasting and careful handling, and that the quantity of fines can be increased substantially depending on the equipment and methods used in handling. Commonly, another 5-percent fines are generated in crushing and processing. Of course, the greater the number of times the material is handled and processed, the greater the percentage of fines generated or material lost (such as in stockpiling).

To minimize further degradation of the materials, the contractor should use large-size loading equipment in the borrow area and rehandling should be kept to a minimum. With large-size loading equipment, it should not be necessary to use dozers on the muck pile. Such use can be expected to cause a significant degradation of the stone particles. Further, the use of large loading equipment minimizes the need of using excessive quantities of explosives to provide excessive rock fragmentation.

Excavation of materials is usually carried out with power shovels, draglines, scrapers, front-end or side-delivery loaders (Sherard, et al., 1963). In quarries, the most common items of equipment are shovels and front-end loaders. Power shovels provide the greatest reaching capacity and greatest digging capacity in poorly fragmented or poorly loosened materials (Fig. 5).

This digging capacity is important when production of large stone is desired for riprap. The reaching capacity often contributes greatly to overall efficiency by permitting higher benches. Large front-end and side-delivery loaders are probably the most economical in a medium-size operation producing crusher feed, where blasting is designed to produce fine fragmentation, and on those projects where high mobility is desirable. (It is a slow process to move a large shovel any distance.) Small front-end loaders are probably the least efficient, since they can only handle small-size

Figure 5. Power shovel loading trucks at Catalina Quarry.

materials in a loosened state. This requires heavy blasting or extensive reworking with a dozer. In all cases, the type of equipment, the capacity, the general handling procedures, and rates of excavations should be documented and the effect of the overall operation on the material gradation evaluated. This is generally done by observing the operation, then sampling and determining the gradation of the material from the muck pile before excavation and after handling by the equipment.

The basic methods of transporting the stone materials are by scrapers, trucks, and belt conveyors. The type of truck generally has little influence on the properties or processing of the embankment material. In recent years, there has been a dramatic increase in the use of conveyor belts, due partly to improvements in belting materials and designs which permit the conveyors to be moved more rapidly. Clearly, lack of mobility is a serious limitation. It is also important to consider carefully the size and gradation of the stone products and the elevation changes required for transport. Most conveyors are easily damaged by large stones and special designs are required in steep topography.

It is not common on construction projects to require cutting and splitting of dimension stone. When such products are required (usually for facing of completed structures), it is customary to purchase these products, as would be done for any other manufactured product. Only a very limited number of sites are suitable for producing dimension stone, and their production requires equipment and skills that are not ordinarily readily available.

5. Placement Methods.

a. General. Stone should be placed by equipment and methods suitable for handling materials of the size specified. Placement of the stone should begin at the bottom of the section and should continue in a manner so as to produce a graded mass of material with maximum interlocking and minimum voids. In general, the larger stones should be placed so that vertical joints are broken with the long axis of the stone set approximately normal to the structure slope and pointing inward toward the center of the structure section. Stone should be placed to the lines and grades shown on the contract drawings. Typical extreme tolerances for finished surfaces, as currently contained in various Corps of Engineers specifications, are ±30 centimeters (12 inches) when placing under water and ±15 centimeters (6 inches) when placing in the dry. Tolerances of ±7.5 centimeters (3 inches) may be required for smaller underlayer and bedding layer stone. Up to 45 centimeters (18 inches) may be allowed for large armor stone. The extremes of tolerances for underlayer stones and large armor stone should generally not be continuous over areas of structure surface greater than approximately 18.5 and 93 square meters (200 and 1 000 square feet) respectively (U.S. Army Engineer Division, North Central, 1978). Rubble-mound structures exposed to wave action during construction should be completed in sections (including placement of armor stone) to minimize damage. Particular care must be taken when building structures such as groins and jetties that pass through the surf zone. Placement of extra stone on and around the end of the structure as it progresses seaward may be required to prevent damaging scour in the surf zone during construction. Damage to unprotected dikes is generally the responsibility of the contractor.

To firmly place stone, particularly in the armor layer, it must be placed or seated on the underlying stones so that it does not tend to slip, tilt, or wobble, either under wave attack or from the weight of stone placed on top of it. This is commonly known as seating the stone. Small armor stone and armor stone placed in areas of very rough seas may have to be randomly placed. If so, design allowance must be made for a less stable structure. Controlled placement methods are preferred for the best use of armor stone; this depends to a great extent on the skill of the contractor personnel.

b. Filter, Bedding, and Core Material. The method used in placement of filter, bedding, or core material should be such that the soft and organic materials on the bottom are displaced outward toward the extreme outside toes of the required sections of the structure and in the direction of the construction. The stone should be handled and placed in such a manner as to minimize segregation and provide a well-graded mass. If the materials are placed by clamshell, dragline, or other similar equipment, the stone should not be dropped from a height exceeding about 0.6 meter (2 feet) above the existing bottom or previously placed material. The use of bottom dump scows and self-unloading vessels may be permitted with the vessel in motion along the centerline of the structure and the material dropped as near to and directly over its final location as possible. The finish surface of the material should be free of mounds or windrows.

In areas where the stone is to be placed on geotextile filter cloth, care should be taken so as not to rupture the cloth and the stone should

not be dropped from a height greater than about 0.3 meter (1 foot). Maximum heights from which stones may be dropped on geotextile filter cloth are specified for varying sizes of stone in Section IX.

c. Underlayer Stone. Underlayer stone should be placed to a uniform thickness in one operation in a manner to avoid displacing the underlying material or placing undue impact force on underlying materials and supporting subsoils. The underlayer stone should be placed in a manner to produce a resultant graded mass of stone with minimum voids. Rearranging of individual stones may be required to achieve this result. Placement by any method which is likely to cause segregation of the various sizes is not permitted. Unsegregated stone can be lowered in a bucket or container and placed in a systematic manner directly on the underlying material. Casting or dropping stone more than 0.6 meter or moving by drifting and manipulating down the slope is generally not permitted (U.S. Army Engineer Division, North Central, 1978).

d. Cover (Armor) Stone. The SPM (U.S. Army, Corps of Engineers, CERC, 1977) and White (1948) show the placement of cover or armor stone as either uniform, special, or random.

(1) Uniform Placement. This is applicable only to concrete armor units and cut or dressed quarrystones in that they are of a uniform size and shape, and thus, lend themselves to an orderly placement pattern. Since quarrystones (as opposed to cut stone) are of random size and shape, uniform placement of quarrystone is impracticable.

(2) Special Placement. This is only applicable to parallelepiped-shaped stone and involves the longest axis being placed perpendicular to the slope of the structure face. For special placement, the longest axial dimension of the stone should be at least twice as long as either of the other two dimensions. The special placement method and the associated stability coefficient should not be used unless quarrystone meets these dimensional specifications, and prospective contractors for the project can assure the developer that they can obtain the quarrystone and place it with the long axis normal to the face of the structure slope.

In general, due to the turbidity of the water at a construction site, the special placement method can only be used above the water surface, as it is not possible to observe or place stones accurately below the water surface using this method. Even then special care must be taken to ensure proper orientation and seating at the interface of the change-in-placement and at the slope-crown interface.

The special placement method will require close inspection and clear instruction to the contractor to ensure proper placement procedures. This method requires more time than random placement and should, therefore, increase the selection, handling, and placement costs of the quarrystone.

(3) Random Placement. Random (formerly pell-mell) placement is a term used to describe a variety of placement techniques ranging from dumping the armor stone under water from a scow to careful, individual placing of the angular quarrystone in the above-water section. Quarrystone placement by a contractor cannot only vary above and below the water level

and along the axis of the rubble structure, but can vary from one job to the next. Placement can also vary from one contractor to another. The variables and difficulties in placing armor units one at a time, or dumping by skiff, above and below water, present the engineer with a difficult design problem. The extent of interlocking achieved is unpredictable when using random size (but still within specified limits) quarrystone. Generally, in specifying quarrystone armor units, the dimension of the maximum axis is no greater than three times the minimum axis. This applies only to armor stone, as this ratio was devised to forestall the use of flat or platelike stone that, if laid flat on the structure slope, would be less stable than a more cubic stone. Because of these unpredictable variables all methods of placement, except for uniform and special placements, have been lumped together as "random placement" to encompass the range of placement methods.

Cover or armor stone should generally be placed individually and in a manner to avoid displacing underlying materials, to avoid placing undue impact force on underlying material, and to minimize chipping the stones (U.S. Army Engineer Division, North Central, 1978) (Fig. 6). The stones should be placed with minimum voids and with maximum interlocking of stones. All stone when placed should be stable, keyed, and interlocked, with no overhanging or "floaters." Keying is the wedging and interlocking of the individual pieces of armor stone so that the individual stone is not only firmly seated but is wedged in by the adjacent armor stones. Keying should not be confused with "chinking" by small nondesign stones. These will be removed by the first severe storm and provide little or no stability. The various sizes of cover stone should be so distributed as to produce a uniform well-graded mass. Adjacent stones should be selected as to size and shape and carefully keyed-in to provide a compact and integrated surface course. Smaller stones should be used to fill the space between larger ones, so as to leave a minimum of voids. Equipment used for placing large stone should be capable of placing the stone near its final position before release and capable of moving the stone if necessary to its final position. Dragline buckets and skips should generally not be used for placement of armor stone. Casting or dropping of stone more than 30 centimeters or moving by drifting or manipulating down the slope should not be permitted (U.S. Army Engineer Division, North Central, 1978). Final shaping of the slope should be performed during placement of stones.

e. Riprap. Stone for "dumped riprap" should be placed on the filter bedding layer or filter cloth in such a manner as to produce a reasonably well-graded mass of rock with the minimum practicable percentage of voids. Riprap should be placed to its full course thickness at one operation and in such a manner as to avoid displacing the bedding material. The larger stones should be well distributed and the entire mass of stones in their final position should be roughly graded to conform to the specified gradation. The finished riprap should be free from objectionable pockets of small stones and clusters of larger stones. Placing riprap in layers should not be permitted. Placing riprap by dumping into chutes or by similar methods likely to cause segregation of the various sizes should not be permitted. The desired distribution of the various sizes of stones throughout the mass may be obtained by selective loading of the material at the quarry or other source, by controlled dumping of successive loads

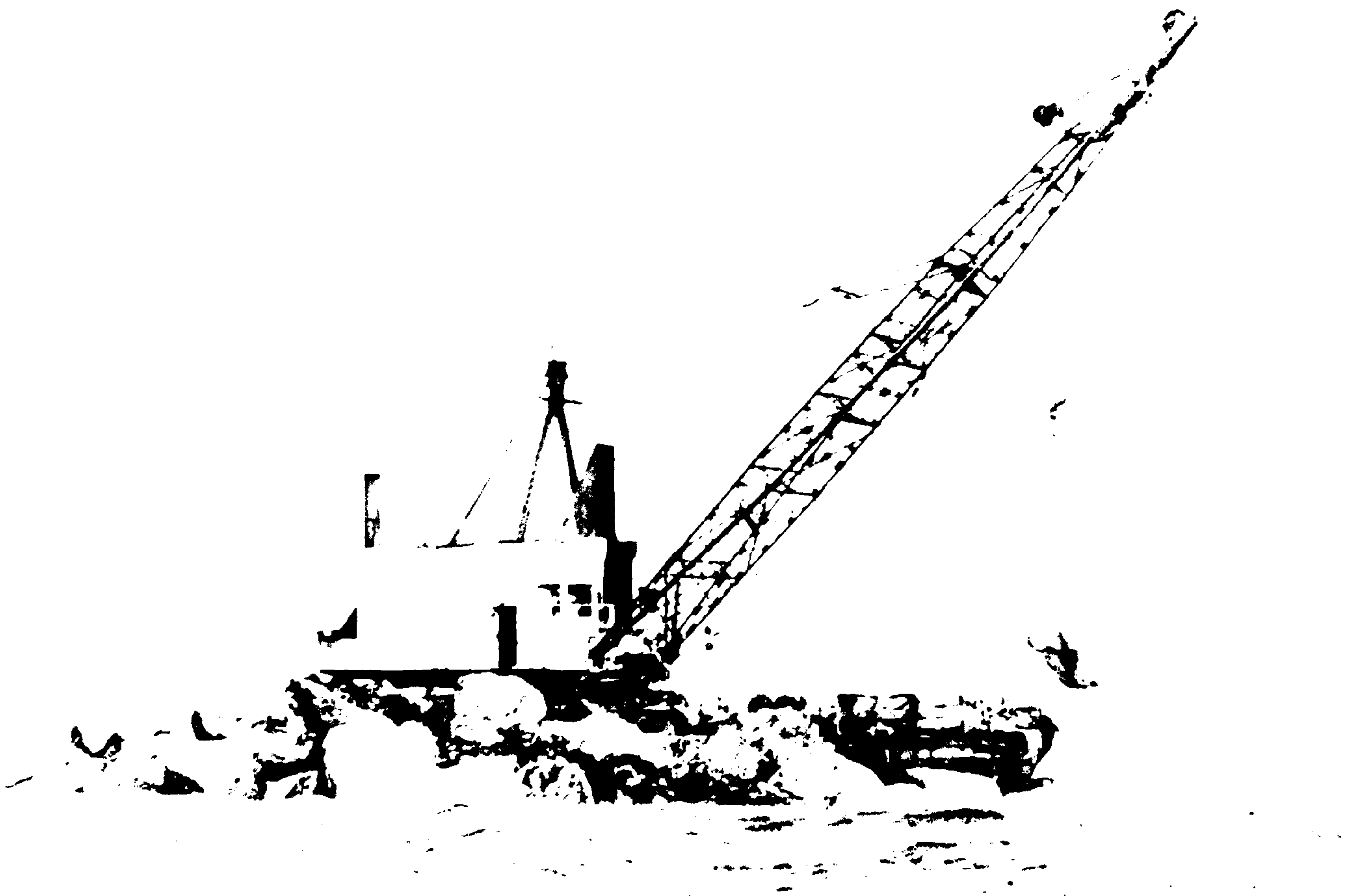


Figure 6. Placing armor stone on jetty, Marina del Rey, California (photo courtesy of William J. Herron).

during final placing, or by other methods of placement which will produce the specified results. Rearranging of individual stones by mechanical equipment or by hand may be required to obtain a reasonably well-graded distribution of stone sizes. Pushing material up the slope or dumping down the slope should not be permitted.

f. Other Stones. Stones to be used as filler material or toe protection stone should be distributed evenly over the required area. Filler stone can be placed on and dumped with core material. Toe protection stone should be placed so as to produce a reasonably well-graded mass of stone with the minimum practicable percentage of voids. Larger stone should be well distributed.

Chink stone should be spread uniformly to form a fairly flat surface, even with the top of the riprap. Placing of materials which tend to segregate particle size should not be permitted. Placement of chink stone may be by hand. In this case the stone should be forced into the riprap voids by rodding, spading, or other satisfactory methods.

6. Repair of Structures.

One of the advantages of stone structures is that they are relatively flexible and are not easily impaired nor weakened by slight movement resulting from settlement or other minor adjustments. Damage to stone structures generally consists of wearing, erosion, dislodging, or removal of the stone. The repair consists primarily of rebuilding the stone structure or replacing the stone with new material. In some cases repair can be achieved with concrete or asphalt grout.

7. Environmental Considerations.

a. General. In its natural environment, most of the varieties of stone normally used in coastal structures are very durable, taking centuries to erode and become part of the sediments of the earth. In coastal structures, this property of durability plus its density is what makes stone a valuable material. Except for the environmental considerations specifically discussed, stone is not significantly affected by the coastal environment.

b. Periodic Wetting and Drying. The gain or loss of moisture when a stone is alternately exposed to a damp or wet situation and then dried will be the most rapid if the pores are large or straight, and least rapid if they are small or tortuous. The leaching action of water which is not chemically combined may remove cementing materials from the stone and weaken it.

c. Freezing and Thawing. Freezing and thawing whether in fresh or salt water can affect the durability of stone. For example, if water is absorbed in the pores of stone and is subsequently frozen, it will expand. The forces developed in filled pores will cause the stone to crack or spall, and the porosity will be increased. As the pores grow, repetition of each cycle will damage the rock. Stone can be disintegrated by freezing and thawing only if the pores are virtually filled with water.

d. Chemical Attack. Calcareous stones are subject to decomposition by acids which may be formed by the combination of moisture and gases, such as sulfur dioxide, which may be present in the air. A sandstone in which the cementing material is calcium carbonate may also disintegrate under such action, whereas a silicate would be more resistant.

e. Rock Borers. Rock borers found in saltwater may penetrate and destroy soft rock such as unconsolidated sandstone and hard clays.

f. Exposure to Waves. Coastal structures are often located so that parts of the structure may be subjected to nonbreaking, breaking, and broken wave forces. Pressure due to nonbreaking waves will be essentially hydrostatic. Breaking and broken waves exert additional pressures due to the dynamic effects of the turbulent water in motion and the compression of entrapped air pockets. These pressures may be much greater than those due entirely to hydrostatic forces. Therefore, structures or parts of structures located in areas in which storm waves may break should be designed to withstand much greater forces and moments than those structures which would be subjected to only nonbreaking waves. Coastal structures may be damaged more by the dislodging of stones from the structure by wave action than by disintegration or breaking of individual stones. The deterioration of stone due to abrasion may be most significant when it is subject to a pounding surf carrying sand, gravel, and smaller stones.

g. Exposure to Ice Floes. An analytical method of determining ice forces on coastal structures is not known (U.S. Army, Corps of Engineers, 1971a); however, some data are available on ice pressures. Floating ice fields may exert a major pressure on maritime structures when driven by strong winds or currents by piling up huge ice masses. Stones frozen to ice sheets may also be carried away by drifting ice. These factors should be considered when designing structures on the Great Lakes and other northern locations.

h. Effects of Temperature and Fire. Stones, like most other materials, expand upon being heated and contract when cooled. Unlike most other materials, however, they do not quite return to their original volume when cooled but show a permanent swelling. This swelling is determined using a coefficient of temperature expansion, which is the change in length per unit length per degree temperature change, for various stones (Mills, Hayward, and Radar, 1955). These coefficients per ^{o} Celsius (^{o} Farenheit) range as follows:

(1) Granites, 0.000 005 60 to 0.000 007 34 (0.000 003 11 to 0.000 004 08);

(2) limestones, 0.000 006 75 to 0.000 007 60 (0.000 003 75 to 0.000 004 20);

(3) marbles, 0.000 006 50 to 0.000 010 12 (0.000 003 61 to 0.000 005 62); and

(4) sandstones, 0.000 009 02 to 0.000 011 96 (0.000 005 01 to 0.000 006 22).

Practically all stones are injured if exposed to such high temperatures as may be encountered in fires, and particularly if exposed to the combined action of fire and water. The cause of disintegration is usually attributed to internal stresses resulting from unequal expansion of unequally heated parts of the material. Experience has shown that granites have a particularly poor resistance to fire and are susceptible to cracking and spalling. This is probably due to the irregularity of the stone structure and the complexity of the mineral composition. The coarse-grained granites are most susceptible to the action of fire and water, and the gneisses often suffer even more severely because of their banded structure.

Limestones suffer little from heat until a temperature somewhat above 100° Celsius (212° Fahrenheit) is reached; at this point the decomposition of the stone begins, due to the driving out of carbon dioxide. The stone then tends to crumble, because of the flaking of the quicklime formed. Marble, due to the coarseness of the texture and the purity of the material, suffers more than limestone. The cracking is irregular, and the surface spalls off similar to that experienced by granites.

Sandstones, especially if of a dense, nonporous structure, suffer from high temperature and sudden cooling less than most other stones. The cracking of sandstones that does occur appears mostly in the planes of the laminations. Sandstones in which the cementing ingredient is silica or lime carbonate are better fire resistants than those in which the grains are bound by iron oxide or clay.

8. Uses In Coastal Construction.

a. Offshore Structures.

(1) Breakwaters. Stone is one of the principal materials used in breakwater building. It is used from the core to the armor in various lifts and layers each having a different gradation. Not all cores are made of stone but when a stone core is used it usually is made of impermeable quarry run stone. The core is covered by a blanket of filter material graded to protect the core from eroding away due to the action of waves and currents and to allow changes of hydrostatic pressure in the core without loss of core material. The next layer is usually the underlayer graded to be stable against the anticipated surge and current action. The final layer of armor stone is placed in the area where waves impinge on the breakwater. Armor stone is graded and sized to remain stable under the impact of unbroken, breaking, and broken waves. Where storm waves may overtop the breakwater, armor stone must be placed on the backslope as well as the seaward face. The elevations and width of crest will depend on the desired use as well as the degree of porosity. Porosity or void ratio is important in dispersing the wave energy and reducing the impact load of the waves striking the breakwaters.

The design size of armor rock for a breakwater is a function of slope, density, and wave height (U.S. Army, Corps of Engineers, 1971a). Hence, the primary concern in the selection of armor stone is density, durability, and available size. Armor stone may be required in pieces varying from about 9 to 270 kilonewtons (1 to 30 short tons). It is usually difficult to quarry, transport, and place stones larger than 270 kilonewtons in size.

Therefore, as design wave heights increase, it becomes more economical to use the more efficient concrete shaped structures such as tetrapods, tribars, and dolos (see Section V).

(2) Fill Material for Caissons. Due to its density and generally low cost, stone fill material is frequently used to ballast caissons and sheet-pile cells. Rockfill should be well graded and free of loam and organic material in order to have the highest density and minimize settlement or, in the case of a perforated caisson, minimize the loss of material due to currents or wave action.

(3) Toe Protection. One of the major causes of failure, or structural damage, of breakwaters has been the undercutting of the toe of the structures. When waves impinge on these structures, they not only exert large impact forces on the armor stone, or face of a vertical structure, but they may also impose strong uplift forces on the lower armor stone and toe stone. Thus, the armor stone must be carried to sufficient depths to resist these forces. An additional problem is the turbulence created in these depths, particularly in the case of waves breaking directly on the structure. This can create scour of the sandy bottom and result in undermining the toe stone resulting in general collapse of the armor layer and exposure of the smaller stone of the underlayers. This can be controlled either by carrying the armor and bedding layers to sufficient depth or the toe section can be overbuilt in anticipation of the quarrystone settling into scour holes. The design of such toe protection is dependent upon wave height and relative depths of the toe protection as compared to the depth of the natural bottom (U.S. Army, Corps of Engineers, CERC, 1977). The same care must be taken as in the design of the rubble structure.

b. Shore-Connected Structures.

(1) Breakwaters, Jetties, and Groins.

(a) General. The primary difference between a breakwater and a jetty or a groin is that the jetty or groin must have a sand-tight core in order to prevent the passage of littoral materials or currents through the structure, whereas breakwaters may be designed to be either permeable or impermeable. All these structures may be subjected to very large breaking or nonbreaking waves. Overtopping of breakwaters and groins in the breaker or uprush zone may be acceptable, but overtopping of jetties must be restricted to prevent passage of sand into navigation channels. Breakwaters connected to shore would otherwise be designed to use stone in the same manner as offshore breakwaters.

(b) Jetties. Jetties are usually constructed from the shoreline through the breaker zone seaward to 12- to 18-meter (40 to 60 foot) depths. They are generally perpendicular to the shoreline. However, due to perhaps as much as a 30° skew, or because of variable wave directions, their alinement may vary from 0° to 90° from the direction of wave travel. Because of variable depths, different parts of the structure may be exposed to unbroken, breaking, or broken waves. Thus with careful design, the elevation, total cross section, and size of armor rock can be varied to produce an economical structure. As jetties are used to define harbor or river access to the sea they may be subjected to major tidal or river

currents or a combination of tidal and river flow. This must be carefully considered, particulary in design of the inner toe of the structure. As the jetties' primary purpose is to prevent the passage of littoral material through the littoral drift zone, the uprush area must be impermeable or sand tight. Other design considerations are much the same as for a breakwater.

(c) Groins. The structural design and the selection of stone sizes and gradation for a groin are much the same as for a jetty. The primary difference is that whereas in a jetty, no sand should pass through or over the structure, most groins are part of a beach stabilization program and it is usually desirable to permit some littoral sand to pass around, over, or through the groin. This is not to imply that the permeability of armor stone can be designed to allow a selected amount of sand to bypass, since current design procedures are not capable of designing successful functioning permeable groins. Many attempts have been made to design groins with a varying degree of permeability. For rubble-stone groins, it is usually adequate to design the elevation of the impermeable core through the nearshore and foreshore area to the desired beach profile. The voids in the armor rock will generally be adequate to pass the surplus sand through to the downdrift beach. Groins usually terminate just seaward of the breaker zone in from 1.8 to 3.6 meters (6 to 12 feet) of water (MLW), and the seaward end is designed against the largest breaking wave possible at that depth, taking tidal elevations into account. The breaker zone is an area of constant turbulence and care must be taken to properly place, as well design, the bedding layer or the structure will fail. Considerable success has been experienced in recent years in replacing this bedding layer of stone (or combining it) with filter cloth.

(2) Seawall or Revetment. A stone rubble seawall or revetment is used to protect the shore, or a shore structure, against erosion by wave action or currents (Fig. 7). It may be a trapezoidal gravity seawall-type structure, backfilled by shore material, or it may be a form of sloped revetment against a shore bank of earth, wood, steel, or concrete.

(a) Current Protection. A revetment designed to protect against currents, tidal or river, is designed much the same as a river revetment except that, in the case of tidal currents, the flow may be reversible. When river and tidal currents combine, tidal elevations must be considered to determine the stage of maximum or critical velocities. Also in bays or large river mouths, consideration must be given to local wind waves, residual swell, or seiching from the open sea. In the case of river mouth entrances, the revetment may simply represent a transition section from the steady flow river revetment to the wave exposed jetty. In other cases, where a jettied entrance connects the open sea to a bay or wide mouth and the channel is of such width as to create currents, the shoreline facing the channel must be revetted. In the same manner as for a breakwater, there must be a layer of armor rock, an underlayer, and a filter layer. Special consideration should be given to ensure stability of the toe of the structure because of the unidirectional flow of most currents.

(b) Wave Protection. The design of a rock rubble face of a seawall or revetment against wave forces is similar to that of the seaward

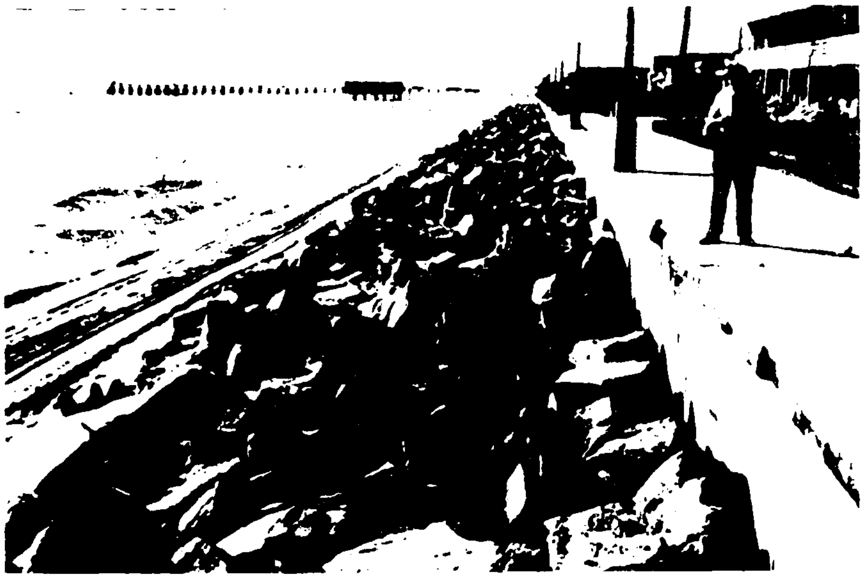


Figure 7. Stone rubble revetment at Jacksonville Beach, Florida.

face of the breakwater. The armor stone must be designed against the force of breaking waves, nonbroken waves, or broken waves. The design size of armor stone will be a function of density, slope, and wave height. In contrast to some breakwaters, almost all seawalls or revetments must be designed to an elevation to prevent wave overtopping. Care must also be taken to construct an adequate toe structure to prevent undermining of the structure during severe wave action. This may not be a serious problem in lakes or bays where advantage can be taken of prolonged periods of small or no wave action to construct the toe trench. Conversely, along the open seacoast, where the action of the surf is continuous, it is generally not possible to excavate to a sufficient depth to reduce scouring velocities. The usual alternative is to overbuild the toe structure in the anticipation that as sand is scoured from under the toe, the excess rock will drop into place and maintain toe support of the structure.

Fixed structures generally have smooth and vertical, or near vertical, faces on the seaward side. The effects of turbulence due to wave action or scouring velocities due to currents can be stronger and more serious on these structures than on rubble structures. In these cases the toe structure can serve two functions:

(1) Designed as a submerged rubble structure, it may rise an appreciable height above the natural bottom and serve to reduce wave or current stresses on the fixed or solid structure (U.S. Army, Corps of Engineers, CERC, 1977); or

(2) designed as a filter blanket or bedding layer, it may be used to prevent scouring of the natural bottom material which might result in undercutting of the wall.

(3) Piers and Wharves. Revetments at pier abutments must be protected the same as any open revetment and in addition must be designed to protect the abutment from loss of foundation. Piers in sandy areas are subject to scour around pilings where strong currents also exist. They can be protected by laying down a quarrystone blanket under the pier in the scour area.

c. Anchors. Deadweight anchors can be any object that is dense, heavy, and resistant to deterioration in water. The type of ocean operation and the availability of materials usually dictate the shape, form, size, and weight of a deadweight anchor. Common examples include stones, concrete blocks, individual chain links, sections of chain links, and railroad wheels. In most instances, a deadweight anchor functions simply as a deadweight on the sea floor that resists uplift by its own weight in water and resists lateral displacement by its drag coefficient with the sea floor. The use of stone as deadweight anchors becomes increasingly impractical as the holding capacity requirement exceeds 6.7 kilonewtons (1 500 pounds).

IV. EARTH

1. Component Types and Class of Soils.

Under the words "earth" or "soil," a large assortment of materials of various origins is covered; for engineering purposes these are generally classified as gravel, sand, silt, clay, and organic material. Most soils are composed of a mixture containing two or more of these materials. Different geological processes (such as alluvial, residual, glacial, or loesial), and parent materials (sedimentary, igneous, and metamorphic) will affect the type and nature of the soils formed. A soil can be described by its grain-size classification, appearance and structure, and compactness or hardness.

There are several soil classification systems, but the most widely used in engineering is the Unified Soil Classification System (USCS). The USCS is presented in the ASTM Standard D2487 and MIL-STD-619A. A summary of the classification system is presented in Table 2 and the general soil characteristics are discussed in the following paragraphs. Table 2-3 in TM S-818-1 is another useful version of USCS. A more detailed presentation of the classification systems and soil properties can be found in the report entitled "Geotechnical Engineering in the Coastal Zone," Callender and Eckert (in preparation, 1983).

a. Coarse-Grained Materials. Gravels and sands are known as coarse-grained soils. Coarse-grained materials are such that 50 percent or more of the materials by weight are retained on the No. 200 sieve. They are recognized either visually and manually or by means of the following parameters:

- Effective grain size (D_{10}): grain size such that 10 percent by weight of the materials are finer.

- Uniformity coefficient (C_u) $= \frac{D_{60}}{D_{10}}$

- Coefficient of curvature (C_c) $= \frac{(D_{30})^2}{D_{10} \cdot D_{60}}$

Because most soils are composed of more than one type of constituent, the USCS makes the following distinctions for sands and gravels:

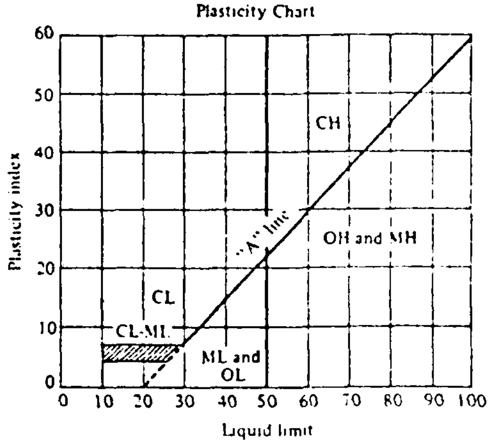
- Well-graded gravel (GW) or sand (SW): all particle sizes are represented within the constituent limits, C_u is greater than 4 or 6, respectively, C_c is between 1 and 3 and the fraction smaller than the No. 200 sieve size does not exceed 5 percent.

- Poorly graded gravel (GP) or sand (SP): some particle sizes are missing or are in excess within the constituent limits, gradation requirements for (GW) or (SW) are not met, and the fraction smaller than the No. 200 sieve size does not exceed 5 percent.

Table 2. Unified soil classification system (ASTM D-2487).

Major Divisions			Group Symbols	Typical Names	Laboratory Classification Criteria		
Coarse-grained soils (More than half of material is larger than No. 200 sieve size)	Gravels (More than half of coarse fraction is larger than No. 4 sieve size)	Clean gravels (Little or no fines)	GW	Well-graded gravels, gravel-sand mixtures, little or no fines	Determine percentages of sand and gravel from grain-size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size), coarse grained soils are classified as follows: Less than 5 per cent: GW, GP, SW, SP; More than 12 per cent: GM, GC, SM, SC; 5 to 12 per cent: *Borderline* cases requiring dual symbols[b]	$C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ between 1 and 3	
			GP	Poorly graded gravels, gravel-sand mixtures, little or no fines		Not meeting all gradation requirements for GW	
		Gravels with fines (Appreciable amount of fines)	GM[a] d / u	Silty gravels, gravel-sand-silt mixtures		Atterberg limits below "A" line or P.I. less than 4	Above "A" line with P.I. between 4 and 7 are *border line* cases requiring use of dual symbols
			GC	Clayey gravels, gravel-sand-clay mixtures		Atterberg limits below "A" line with P.I. greater than 7	
	Sands (More than half of coarse fraction is smaller than No. 4 sieve size)	Clean sands (Little or no fines)	SW	Well-graded sands, gravelly sands, little or no fines		$C_u = \frac{D_{60}}{D_{10}}$ greater than 6; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ between 1 and 3	
			SP	Poorly graded sands, gravelly sands, little or no fines		Not meeting all gradation requirements for SW	
		Sands with fines (Appreciable amount of fines)	SM[a] d / u	Silty sands, sand-silt mixtures		Atterberg limits above "A" line or P.I. less than 4	Limits plotting in hatched zone with P.I. between 4 and 7 are *borderline* cases requiring use of dual symbols
			SC	Clayey sands, sand-clay mixtures		Atterberg limits above "A" line with P.I. greater than 7	
Fine-grained soils (More than half material is smaller than No. 200 sieve)	Silts and clays (Liquid limit less than 50)		ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity	Plasticity Chart (see below)		
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays			
			OL	Organic silts and organic silty clays of low plasticity			
	Silts and clays (Liquid limit greater than 50)		MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts			
			CH	Inorganic clays of high plasticity, fat clays			
			OH	Organic clays of medium to high plasticity, organic silts			
	Highly organic soils		Pt	Peat and other highly organic soils			

Plasticity Chart



[a] Division of GM and SM groups into subdivisions of d and u are for roads and airfields only. Subdivision is based on Atterberg limits; suffix d used when L.L. is 28 or less and the P.I. is 6 or less; the suffix u used when L.L. is greater than 28.

[b] Borderline classifications, used for soils possessing characteristics of two groups, are designated by combinations of group symbols. For example: GW-GC, well-graded gravel-sand mixture with clay binder.

- Silty gravel (GM) or sand (SM): more than 12 percent by weight are finer than No. 200 sieve, and the fines have little or no plasticity.

- Clayey gravel (GC) or sand (SC): more than 12 percent by weight are finer than the No. 200 sieve, and the fines are plastic.

When the fraction smaller than the No. 200 sieve size is greater than 5 percent and less than 12 percent, a dual symbol should be used.

Well and poorly graded gravels and sands are further defined as clean gravels or sands; silty or clayey gravels and sands may be referred to as dirty gravels or sands. It should also be noted that the particle shape has an influence on the density and the stability of the coarse-grained soils.

(1) Gravel (G). The USCS defines gravel as the material whose size ranges between 76.2 millimeters (3 inches) and the No. 4 Sieve. Materials larger than 76.2 millimeters are designated as cobbles. Gravels may be man-made (crushed stone) or may come from natural deposits (bank-run). Gravels are cohesionless materials.

(2) Sand (S). A material is defined as sand when its grain size is between 4.76 and 0.075 millimeter (No. 4 and 200 sieves, respectively). The USCS developed further classification: the sand is coarse when its grain size varies between 4.76 and 2.00 millimeters (No. 4 and 10 sieves, respectively); medium when between 2.00 and 0.42 millimeter (No. 10 and 40 sieves, respectively); and fine when between 0.42 and 0.075 millimeter (No. 40 and 200 sieves, respectively). Sands are cohesionless materials, however, they present an apparent cohesion when damp or moist due to surface tension effects of pore fluids. These effects disappear when the sand is saturated.

b. Fine-Grained Materials. Silts and clays are known as fine-grained soils. Fine-grained materials are such that 50 percent or more of the materials by weight pass the No. 200 sieve. They are distinguished either visually and manually or by means of the Atterberg limits. The USCS, contrary to most other classification systems, does not make any size distinction between silt and clay. This is because the engineering properties of fine-grained soil are more closely related to plasticity characteristics than to grain size.

The USCS distinguishes the following:

- Silt, clay, and organic silt and clay having liquid limits less than 50: ML, CL, and OL, respectively.

- Silt, clay, and organic silt and clay having liquid limits greater than 50: MH, CH, and OH, respectively.

Fine-grained soils usually have a low permeability (10^{-7} to 10^{-3} centimeter per second) with silty soils being somewhat more permeable than clayey ones. Organic materials tend to lower the strength characteristics of the soil, lower the maximum density, increase the time for consolidation and increase the optimum water content.

(1) Silt (M). Silt is a fine-grained soil of low plasticity which may exhibit an apparent cohesion due to capillary forces. Silts have relatively poor strength characteristics, except when they are dry or in the form of siltstones and are poor foundation materials in cold climates due to frost heave. Confined, relatively dense silts may perform satisfactorily as foundation soil, but must be evaluated on a case by case basis. Most coastal silts are found in combination with some clay which will increase cohesion and improve foundation characteristics.

(2) Clay (C). Clay is distinguished by its fine particle size and cohesive strength which is inversely related to its water content. For this reason, a clay's performance as a foundation material is strongly influenced by its stress history. In situ overconsolidated clays, clays which have been loaded to higher stresses than the present load may perform quite well in foundations. Normally consolidated or underconsolidated clays typical of estuaries will generally experience large settlements when loaded. The minerals included in the clay composition influence the properties of the soil; e.g., montmorillonite is a highly active mineral, and a soil containing such a mineral will present high swelling and shrinkage characteristics. Two other commonly occurring minerals are illite (less active than montmorillonite and commonly found in marine clays) and kaolinite (the least active mineral).

c. Organic Materials (O). Peat, organic mulch, and muskeg are highly organic soils which usually have a spongy nature and a fibrous texture. Organic materials come from the decay of vegetable matter. They are recognized by their odor, which is intensified by heating, and by their dark color (although some dark soils may be inorganic). Usually organic soils have high moisture and gas contents and a relatively low specific gravity.

2. Properties and Characteristics of Soils.

The major significant engineering properties of soil are shear strength, compressibility, and permeability. The types of geotechnical problems encountered in the design of coastal structures which utilize these characteristics are slope stability, bearing capacity, settlement and erosion. A detailed discussion of the properties and characteristics of soils and the tests required to determine them can be found in Geotechnical Engineering in the Coastal Zone (Callender and Eckert, in preparation, 1983). The potential contaminants derived from industrial wastes, such as toxic heavy metals (mercury, cadmium, lead, and arsenic), chlorinated organic chemicals (DDT and PCB's) and pathogens (bacteria, viruses, and parasites) should also be considered in the evaluation of the use of any soil in coastal structures. In general "polluted" soils should not be used.

a. Shear Strength. The three types of tests commonly performed to determine soil strength are designated as

(1) Unconsolidated-Undrained triaxial test, commonly known as a UU-Test or Q-Test,

(2) Consolidated-Undrained triaxial test, commonly known as a CU-Test or R-Test, and

(5) Consolidated-Drained triaxial test, commonly known as a CD-Test or S-Test.

The Q, R, and S designations are standard use in Corps literature. The descriptions are indicative of the conditions under which the tests are run. From the results of these tests the stress-strain characteristics are established under the various loading conditions noted, and of equal importance, the conditions of failure for the soil are established. The strength of a soil is usually defined in terms of the stress developed at the peak of the stress-strain curve and is presented in the form of Mohr circles and a Mohr failure envelope. The strength is then expressed in terms of cohesion and the angle of internal friction.

b. Compressibility. The simplest compressibility or consolidation test is the one-dimensional, laterally confined compression test (often referred to as oedometer test). In this test the soil sample is placed within a restraining ring and loaded with special types of plates on either top or bottom or both. The change in sample height is measured by a deflection gage and is used to calculate the change in void ratio (e) at different normal pressures (P). If the soil is saturated, the sample is placed between two porous disks that permit the water to drain away during compression. This in turn leads to information which permits plotting of the so-called e-log P relationship. From such plots for either sands, silts or clays, or mixtures of them, normally moduli are estimated which can then be used for consolidation and settlement estimates. It should be emphasized that in such tests the lateral expansion is restrained. In real situations this is only approximated by the loading of relatively thin layers of compressible soil through load distribution over a large area.

(1) Compressibility of Sands. The most important property of the sand, which governs the stiffness of the sand, is relative density. The relative density of the sand is usually determined in the field by means of standard penetration tests or Dutch cone penetration tests.

(2) Compressibility of Clays and Silts. The predictions of static settlement of silts and clays are usually made on the basis of consolidation or oedometer tests. The rate of settlement and the time for essential completion of primary consolidation can be predicted on the basis of this test. Typically, silts are less compressible than clays.

c. Permeability. Permeability is the soil property that indicates the relative ease with which a fluid will flow through the soil. The coefficient of permeability (k) of a soil is defined as the average percolation velocity (v) divided by the hydraulic gradient (i) in the soil at that particular point. It is seen then that the coefficient of permeability has units of velocity, commonly centimeter per second or foot per minute. Permeability depends on the characteristics of both the pore fluid and the soil. Viscosity, unit weight, and polarity are the major pore fluid characteristics. Particle size, void ratio, composition, fabric, and degree of saturation are the major soil characteristics. In general a qualitative approximation of the permeability of the materials can be made on the basis of grain size. For example, clean gravels will have permeabilities ranging from 10^{+1} to 10^{+2} centimeters per second. Clean medium to coarse sands will have permeabilities ranging from 10^{-2} to 1 centimeter per second. Very fine sand

Figure 8. Reinforced earth seawall construction at Petersburg, Alaska (Photo courtesy of The Reinforced Earth Company).

will have permeabilities ranging from 10^{-3} to $10^{-[illegible]}$ centimeters per second. Organic and inorganic silts, mixtures of sand, silt and clay, glacial till, and some stratified clay deposits will have permeabilities ranging from $10^{-[illegible]}$ to 10^{-5} centimeters per second. Clays, which are practically impervious and commonly used for core materials in water-retaining embankments, will have permeabilities ranging from 10^{-9} to 10^{-7} centimeters per second.

d. Other Properties and Characteristics. Other soil properties and characteristics that are useful to know for the design of coastal structures include dry density, water content, specific gravity, resistivity and corrosion potential, grain-size distribution, plasticity characteristics, chemical properties, and durability.

3. Methods of Soil Improvement.

Methods of soil improvement generally include densification, drainage, changing soil properties at depth by grouting or injection, surface stabilization by admixtures, and reinforcement with metal or fabric strips or mesh. Most of these methods have been utilized in one manner or another to improve soils used in the construction of coastal structures. The most widely used, and generally the most practical, are densification and drainage. A somewhat newer method developed in Europe, and now being more widely used in the United States is reinforced earth (Figs. 8 and 9). Some of the methods available for improvement of soils are classified according to the basis of soil improvement, as shown in Table 3 (Mitchell, 1976).

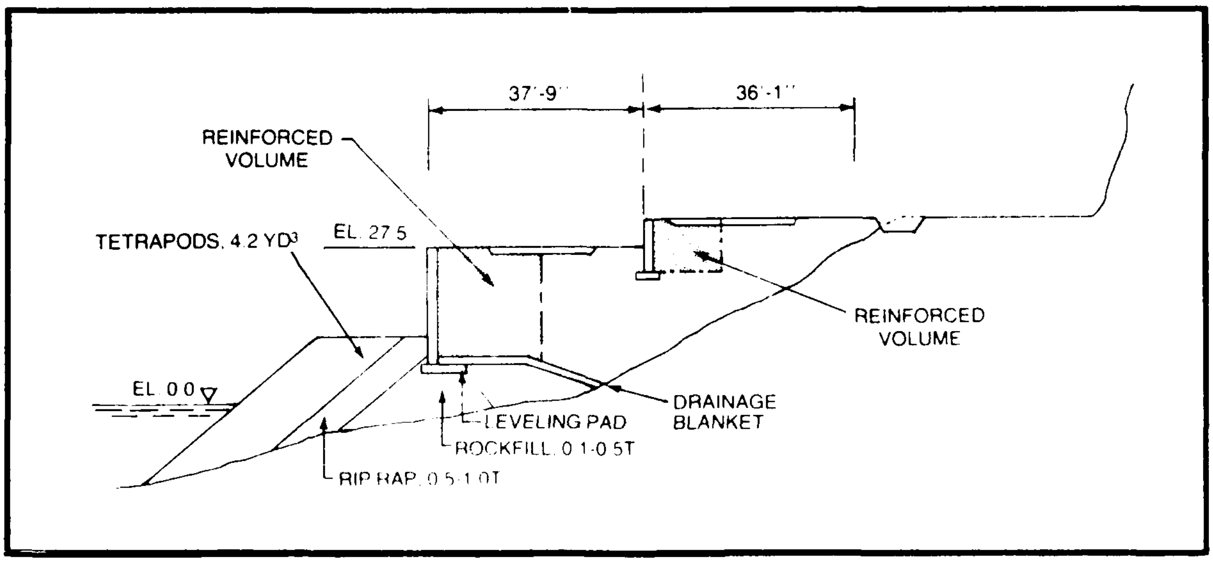


Figure 9. Cross section of reinforced earth seawall at LaReunion Island in the Indian Ocean (courtesy of The Reinforced Earth Company).

Table 5. Improvement of soils for coastal construction.

METHOD	PRINCIPLE	MOST SUITABLE SOIL CONDITIONS/ TYPES	SPECIAL MATERIALS REQUIRED	SPECIAL EQUIPMENT REQUIRED	PROPERTIES OF TREATED MATERIAL	SPECIAL ADVANTAGES AND LIMITATIONS
BLASTING	Shock waves and vibrations cause liquefaction, displacement, remolding	Saturated, clean sands, partly saturated sands and silts after flooding	Explosives, backfill to plug drill holes	Jetting or drilling machine	Can obtain relative densities from 70 to 80 pct; may get variable density	Rapid, inexpensive, can treat small areas; variable properties, no improvement near surface, dangerous
TERRAPROBE	Densification by vibration; liquefaction induced settlement under overburden	Saturated or dry clean sand	None	Vibratory piledriver and 750-mm-dia. open steel pipe	Can obtain Relative Densities of 80 pct or more	Rapid, simple, good underwater; soft underlayers may damp vibrations, difficult to penetrate, stiff overlayers, not good in partly saturated soils
VIBRATORY ROLLERS	Densification by vibration; liquefaction induced settlement under roller weight	Cohesionless soils	None	Vibratory roller	Can obtain very high relative densities; upper few decimeters not densified	Best method for thin layers or lifts
COMPACTION PILES	Densification by displacement of pile volume and by vibration during driving	Loose sandy soils; partly saturated clayey soils; loess	Pile material (usually sand or soil plus cement mixture)	Piledriver	Can obtain high densities, good uniformity	Useful in soils with fines, uniform compaction, easy to check results; slow, limited improvement in upper 1 to 2 m
HEAVY TAMPING (Dynamic Consolidation)	Repeated application of high intensity impacts at surface	Cohesionless soils best, other types can also be improved	None	Tamper of 10 to 40 tons, high-capacity crane	Can obtain high relative densities, reasonable uniformity	Simple, rapid, suitable for soils with fines; usable above and below water; requires control, must be away from existing structures
[illegible]	Densification by vibration and compaction of backfill material	Cohesionless soils with less than 20 pct fines	Granular backfill	Vibroflot, crane	Can obtain high relative densities, good uniformity	Useful in saturated and partly saturated soils uniformity

Table 5. Improvement of soils for coastal construction--Continued.

METHOD	PRINCIPLE	MOST SUITABLE SOIL CONDITIONS/ TYPES	SPECIAL MATERIALS REQUIRED	SPECIAL EQUIPMENT REQUIRED	PROPERTIES OF TREATED MATERIAL	SPECIAL ADVANTAGES AND LIMITATIONS
PARTICULATE GROUTING	Penetration grouting: fill soil pores with soil, cement, or clay	Medium to coarse sand and gravel	Grout, water	Mixers, tanks, pumps, hoses	Impervious, high strength with cement grout, eliminate liquefaction danger	Low cost grouts, high strength, limited to coarse-grained soils, hard to evaluate
CHEMICAL GROUTING	Solutions of two or more chemicals react in soil pores to form a gel or a solid precipitate	Medium silts and coarser	Grout, water	Mixers, tanks, pumps, hoses	Impervious, low to high strength, eliminate liquefaction danger	Low viscosity, controllable gel time, good water shutoff, high cost, hard to evaluate
PRESSURE INJECTED LIME	Lime slurry injected to shallow depths under high pressure	Expansive clays	Lime water, surfactant	Slurry tanks, agitators, injection	Lime-encapsulated zones formed by channels resulting from cracks, root holes, hydraulic fracture	Rapid and economical treatment for foundation soils under light structures
DISPLACEMENT GROUT	Highly viscous grout acts as radial hydraulic jack when pumped in under high pressure	Soft, fine-grained soils; foundation soils with large voids or cavities	Soil, cement, water	Batching equipment, high-pressure pumps, hoses	Grout bulbs within compressed soil matrix	Good for correction of differential settlements, filling large voids; careful control required
PRELOADING	Load is applied sufficiently in advance of construction so that compression of soft soils is completed prior to development of the site	Normally consolidated soft clays, silts, organic deposits, completed sanitary landfills	Earthfill or other material for loading the site; sand or gravel for drainage blanket	Earth-moving equipment; large water tanks or vacuum drainage systems sometimes used; settlement markers, piezometers	Reduced water content and void ratio, increased strength	Easy, theory well developed, uniformity; requires long time (sand drains or wicks can be used to reduce consolidation time)
SURCHARGE FILLS	Fill in excess of that required permanently is applied to achieve a given amount of settlement in a shorter time; excess fill then removed	Normally consolidated soft clays, silts, organic deposits, completed sanitary landfills	Earthfill or other material for loading the site; sand or gravel for drainage blanket	Earth-moving equipment; settlement markers, piezometers	Reduced water content, void ratio and compressibility; increased strength	Faster than preloading without surcharge, theory well developed; extra material handling; can use sand drains or wicks

Table 3. Improvement of soils for coastal construction--Continued.

METHOD	PRINCIPLE	MOST SUITABLE SOIL CONDITIONS/ TYPES	SPECIAL MATERIALS REQUIRED	SPECIAL EQUIPMENT REQUIRED	PROPERTIES OF TREATED MATERIAL	SPECIAL ADVANTAGES AND LIMITATIONS
DYNAMIC CONSOLI-DATION	High-energy impacts compress and dissolve gas in pores to give immediate settlement; in-creased pore pressure gives subsequent drain-age	Partly satu-rated fine grained soils, quaternary clays with 1 to 4 pct gas in micro bubbles	None	Tamper of 10 to 40 tons high capacity crane	Reduced water content, void ratio and com-pressibility; increased strength	Faster than pre-loading, econo-mical on large areas; uncertain mechanism in clays, less uniformity than preloading
MIX-IN-PLACE PILES AND WALLS	Lime, cement, or asphalt intro-duced through ro-tating auger or special in-place mixer	All soft or loose inorganic soils	Cement, lime, asphalt, or chemical stabilizer	Drill rig, rotary cutting and mixing head, additive pro-portioning equipment	Solidified soil piles or walls of relatively high strength	Uses native soil, reduced lateral support require-ments during ex-cavation; diffi-cult quality con-trol
STRIPS AND MEMBRANES	Horizontal tensile strips or membranes buried in soil un-der footings	All	Metal or plastic strips, polyethylene, polypropylene, or polyester fabrics	Excavating, earth handl-ing, and compaction equipment	Increased bearing capacity, reduced deformation	Increased allow-able bearing pressure; requires over-excavation for footings

4. Placement of Soil for Coastal Structures.

Earthfills for coastal developments can be placed from the land by dumping or shoving into place, from water by deck and bottom-dump barges, or hydraulically from dredging operations. The method and equipment used depends on the type and source of material, the area of placement (above or below the water level), the depth of water (for operating bottom-dump barges), the purpose and design of the structure or fill, the availability of equipment, the impact on the environment, and the economics of the operation. The material may also be placed with or without compaction to alter the soil density.

a. Dumped Loose Fills. Soils obtained from land sources are typically transported by and dumped from trucks, scrapers, conveyor belts, or possibly shovels. The materials are then shoved into place and leveled. Soils obtained from marine sources are typically excavated by shovels, draglines or bucket-dredge, and either dumped directly in place or placed in trucks or barges and transported to the site. The soils placed in trucks would be dumped the same as a landfill. Soils placed in barges would be transferred to shore equipment or dumped through the water (Fig. 10). Soils placed in this latter manner will typically have low to medium relative densities.

The placement of fill landward of a bulkhead driven into a mud bottom may result in the formation of mud waves. Such mud waves can progress

Figure 10. Fill being placed by tilt barge at Redondo Beach, California (photo courtesy of Woodward-Clyde Consultants).

ahead of the advancing fill and overload the bulkhead causing its failure before the landfill reaches it. The mud should be removed before fill placement or the bulkhead designed for the increased pressures of the mud wave. Care should also be taken to place select fill behind the bulkhead before placing the general fill to ensure that the active pressure zone has the shear strength planned in the design.

Excessive turbulence in dumping fill material through water should be avoided in order to prevent segregation of the materials or extremely flat slopes at the edge of a fill. Uncontrolled bottom dumping from barges through great depths of water will encourage segregation and spread fill over a wide area. Berms or dikes of coarse-grained material or stone can be used to confine the material.

b. Compacted Fills. Where compaction of fills above the water level is desired, either the method of compaction or the desired compaction can be specified. A test section is usually required to determine the effectiveness of the methods before specifying a particular method. Otherwise, the required density, moisture limits, and lift thickness are specified, allowing the contractor some selection in compaction methods.

Coarse-grained, cohesionless soils with less than 4 percent passing a No. 200 sieve for well-graded soils, or with less than 8 percent for uniform gradation, are generally insensitive to compaction moisture. These soils should be placed at the highest practical moisture content and compacted by vibratory methods. Where materials with sizes up to 150 millimeters (6 inches) maximum are used, the large sizes will interfere with the compaction of soil smaller than a No. 4 sieve or 19-millimeter (0.75 inch) size. Where large parts (more than 30 percent by weight) of gravel and cobbles are present, a slight reduction (several percent) in the required density of the sizes smaller than a No. 4 sieve may be tolerated.

c. Hydraulic Fills. Hydraulic fills are placed on land or under water by pumping material through a pipeline or by water sluicing through a conveyor. Borrow materials used for these fills are generally obtained by dredging (Fig. 11). The characteristics of such hydraulic fills may be generally classified according to the nature of the borrow material (Whitman, 1970). This classification is shown in Table 4.

Generally, material with more than 15-percent nonplastic fines or 10-percent plastic fines passing a No. 200 sieve should not be placed under water. The wash water for hydraulically placed fills on land should run off in such a manner that fines are not concentrated in pockets. This may require advancing the fill from one side or corner of the area, attempting to force out any soft fines ahead of the fill as it is placed. Hydraulic fills placed behind walls or bulkheads should be placed in lifts thin enough to permit runoff of wash water without building up a full height of hydrostatic pressure.

Dredging and handling operations will produce significant textural differences between original bottom sediments and sediments deposited at the fill site. In general, these differences are an increase in the mean grain size as fines are lost and a decrease in the uniformity coefficient (see Table 2) of delivered versus bottom sands. The volumetric losses

resulting from winnowing associated with this process appear to be on the order of 10 percent or more, depending on the original bottom material.

d. Artificial Beach Restoration. The placement of sandfill along a part of shore front for beach restoration may be done in three ways. It may be placed directly onto the shore to be protected or developed as a beach; it may be placed in an area adjacent to and updrift of the area to be protected; or it may be placed offshore. That is, it may be directly placed, placed to form a feeder beach (designed to be eroded by waves and tidal currents and transported via longshore transport to the area to be protected), or placed as a bar (designed to be transported inshore by waves and currents). To be effective, offshore restoration must involve placing fill in the zone where shoreward movement of the sand occurs, piling it as high as possible, and placing it during the spring or early summer to take full advantage of the seasonal beach building before the annual period of steep winter storm waves.

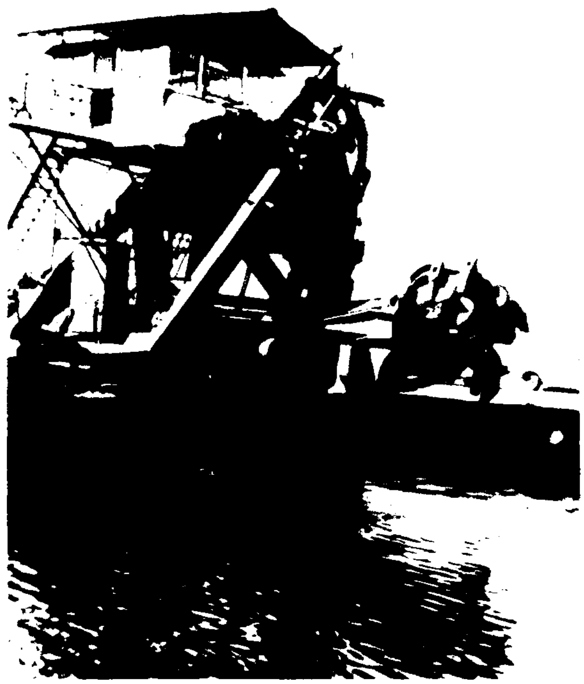


Figure 11. Dredge Chequinquira at dock (photo courtesy of Woodward-Clyde Consultants).

Table 4. Characteristics of fill based on nature of borrow material.

Nature of Borrow Material	Characteristics of Fill
Fairly clean sand	Reasonably uniform fill of moderate density (relative density of 40 to 60 percent)
Silty or clayey sand	Very heterogeneous fill of large void ratio (low relative density)
Stiff cohesive soil	Skeleton of clay balls, with matrix of sand and clay
Soft cohesive soil	Laminated normally consolidated or unconsolidated clay.

5. Repair of Earth Structures.

Damage to earth structures or earth parts of structures generally consists of erosion or removal of the soil. The repair consists primarily of replacing the earth material or the protective layer. If permeability or stability of the structure is a problem, the voids can be filled with concrete or asphalt grout.

6. Environmental Considerations.

a. Physical Effects. The nature of the soil pore fluid and temperature can influence the behavior of clay soils. A loss in shear strength of marine clays may be realized by removal of the salt due to leaching by freshwater. Changes in moisture content can cause swelling or shrinking of clay soils. Decreasing the temperature of a cohesive soil can cause an expansion of the soil. Fine-grained soils are also susceptible to frost heave.

The most significant environmental effect on the physical properties of soils is liquefaction (resulting in loss of strength) due to a seismic event or water wave action. Liquefaction due to either of these causes could result in failure of the structure. The soil properties generally related to this phenomona are saturation, grain size, relative density, and permeability. The problem is generally associated with loose fine sands and silts below the water level at sites in highly seismic areas or areas subject to high breaking waves. Liquefaction of foundation soils under gravity ocean structures due to water wave forces on the structure has been found in offshore work. Liquefaction can generally be minimized or mitigated by densification or treatment of the soils, or by providing drainage (rock drains). A discussion of soil response to both seismic and water wave-induced dynamic loads is presented in Callender and Eckert (in preparation, 1983).

b. Erosion Effects. The erosion and subsequent deterioration of both natural landforms and manmade coastal structures is of concern. Shore erosion is a major problem along the ocean coastline and the Great Lakes. Erosion is caused principally by storm-induced wave action and associated longshore currents. The processes are further complicated by erosive forces that may come from ice, wind, rain, burrowing animals, or human activity. Shore erosion problems become more critical when beaches become eroded or submerged, and adjoining highly erodible upland areas are subject to direct wave attack (Fig. 12). Unconsolidated sands and silts are generally the most easily eroded, clays and gravels are slightly more resistant, and cemented soils and rock are the least erodible earth materials. The soils may be protected from erosion by various devices such as revetments, seawalls, and bulkheads. Groins may be used to maintain beaches. A detailed discussion of beach erosion is presented in Chapter 4 of the SPM (U.S. Army, Corps of Engineers, CERC, 1977).

7. Uses of Soils in Coastal Construction.

a. General. Earth can be used for almost any kind of coastal structure. Coastal structures are generally associated with three types of projects: port and harbor development (including marinas), land reclamation, and coastal protection. Design considerations and criteria are

Figure 12. Wave erosion of Sunset Cliffs in San Diego, California (photo courtesy of City of San Diego).

discussed in detail in Callender and Eckert (in preparation, 1983). Soils are used in coastal structures for backfill materials, core materials, slopes and beach restoration. The use of the material is generally associated with the type of development and the type of structure. The choice of material depends on the economy and availability of the material, depth of water, expected water or wave forces, and the purpose of the structure. Some of the various uses are presented in the following paragraphs.

b. Offshore Construction.

(1) Breakwaters. In rubble-mound breakwaters, submerged reefs, and other coastal rock structures, sand may be used as core material providing other materials are used to protect against wave damage and piping. Clay may be mixed with the sand to reduce permeability, but is generally not adequate core material by itself. The structures may be designed as permeable or impermeable. The soils are usually dredged materials and are placed hydraulically. The core may be covered with filter material and quarrystone riprap or armor units; the number of covering layers depends on the water depth, the design storm waves, and the desired degree of permeability.

(2) Caissons. Concrete caissons and sheet-pile cells may be filled with sand and clay. If the surface is to be paved and used for load bearing, sand is preferable to clay because of its higher bearing capacity. A filter layer and armor rock must be provided to cover the fine soils where waves or water currents are expected to impinge on earthfill.

c. Shore-Connected Construction.

(1) Breakwaters, Jetties and Groins. These structures of rubble-mound construction, caissons, or sheet-pile cells may be filled with soil as described for offshore construction.

(2) Low-Cost Shore Protection, Fabric Bags. Low-cost groins and breakwaters have also been constructed by means of fabric bags filled with medium sand or sand-cement. The bags are generally made of nylon, and may be coated with polyvinyl chloride or acrylic to delay fiber degradation by ultraviolet rays. The bags may be filled with available beach sand and used as a low-cost shore protection device. The bags may be filled using a 19-millimeter diaphragm pump or, for more efficiency, a small front-end loader, a hopper, and a jet pump. Typical filled bags measure approximately 3 by 1.5 by 0.5 meter (10 by 5 by 1.5 feet), hold about 1.9 cubic meters (2.5 cubic yards) of sand, and weight about 31 kilonewtons (7 000 pounds). The sand used should be saturated so as to eliminate air pockets which would cause a buoyant force on the bags. Small bags filled with sand (Fig. 13) or concrete (Fig. 14) may be used for protection against erosion.

(3) Bulkheads, Quaywalls, and Seawalls. Usually soil materials are used as backfill or foundation materials for bulkheads and walls. Their primary purpose is to provide a level surface or to fill a void behind the structure. The materials can be placed from land, end-dumped from trucks or conveyor belts, or they can be placed hydraulically from dredges; however, the relative density achieved by each method may be widely different. The backfill may be composed of a mixture of all or part

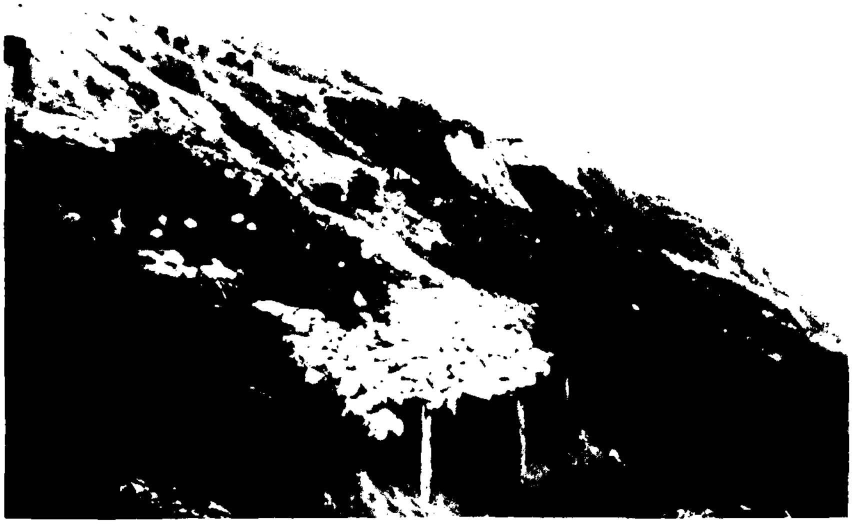


Figure 13. Sea cliff upper slope erosion protection by cloth bags filled with sand supported by wood bulkheads, Luecadia, California (photo courtesy of Woodward-Clyde Consultants).

Figure 14. Sea cliff shore protection by cloth bags filled with concrete placed in soil bank, Solano Beach, California (photo courtesy of Woodward-Clyde Consultants).

of the four component types of soil (gravel, sand, silt, clay); however, not all soil mixtures are equally effective in a given situation. Organic materials are usually considered detrimental and are not used, since they tend to be more compressible and have lower shear strengths. Highly expansive clay should also generally not be used for backfill of coastal structures.

A filter layer of gravel or crushed stone is often used (with or without a geotextile filter) under and behind walls to provide for relief of hydrostatic pressure and to prevent piping. These materials should meet filter design criteria.

(4) Wharves and Piers. The use of earth for wharves and piers is generally as fill behind or for slopes underneath the facility. The natural in-place soils generally provide support for the structures, and foundations are designed in accordance with conventional geotechnical procedures. The purpose of the fill is to help provide stability and rigidity to the structure and to provide useful working areas behind the structure. Most soils may be used for this purpose, but they generally need some type of protection, such as rock riprap and a filter, to mitigate erosion. Coarse-grained granular soils are preferable for use as backfill materials, since they are typically stronger and less compressible. The properties of the backfill soils of use in the design include dry density, water content, shear strength, and compressibility. Other important properties may be the compaction characteristics, permeability, and corrosive characteristics.

(5) Land Reclamation. Land reclamation may include dredging for marinas, construction of fills for water-oriented land developments, enlargement of streams, and other related activities in waters and wetlands. These activities generally involve discharge of fill material onto the adjacent shoreline or into waters or wetlands for construction of structures; site development fills for recreational, industrial, commercial, residential, and other uses; causeways or road fills; dams and dikes; artificial islands, property protection; groins and beach restoration; levees and artificial reefs. These fills may be obtained from land sources and dumped by land methods or from water sources and placed hydraulically by dredging. The properties of soils most useful to know in land reclamation projects are the strength characteristics, consolidation characteristics, and chemical properties after placement of the fill.

(6) Dikes. Dikes can be constructed of sand, clay, or a combination of both. Earth dikes are usually utilized as containment structures for dredged materials, but may also be used as protective devices such as hurricane barriers. They generally require some type of protection when subjected to wave action. Clay dikes and dikes with a sand core and clay cover have also been built with seaward slopes of 1:6 to 1:10 with a grass cover.

(7) Protective Beach and Dune Restoration. The placement of sandfill along a part of shore front is a nonstructural erosion control technique, referred to as beach nourishment, that is utilized for the protection of beach areas or for the creation of protective beaches in areas where none exist. Artificial restoration projects should generally define the source of material, the method of placement, and the grain-size

distribution and amount of sand. The sources of material may be either from land or offshore. The methods of placement include placing sand directly on the beach along the entire length of the project, placing it in stockpiles at a feeder beach at one end of the site, and placing it as an offshore bar. The grain size of the materials used should be larger than, or at least the same size as, the original beach material. If coarser sands are used in the beach restoration, the equilibrium slope will be steeper than the existing one, and vice versa for finer particles. A more detailed presentation on beach nourishment may be found in Chapters 5 and 6 of the SPM (U.S. Army, Corps of Engineers, CERC, 1977).

A subsand filter system (gravel filter bedding layer placed in the foreshore or offshore zones) may be useful in the stabilization of offshore profiles. Preliminary studies have indicated that such filters may have a stabilizing effect on the bed material in the offshore zone and that they may be effective in speeding accretion in the foreshore zone. The latter use may be employed for berm building or berm replacement (Machemehl, French, and Huang, 1975).

The construction of dunes is another type of nonstructural erosion mitigation. Dunes are constructed or enhanced by the placement of sandfill and by the planting of stabilizing vegetation. Snow fences may also be used to physically retain initial sand. Dunes are generally constructed parallel to and behind the beach proper and serve to trap and absorb sand which is transported by onshore winds, storm overwash, or offshore winds blowing over overwash plains. The construction and stabilization of sand dunes is discussed in Chapters 5 and 6 of the SPM (U.S. Army, Corps of Engineers, CERC, 1977).

V. PORTLAND CEMENT CONCRETE

1. Introduction.

Concrete, a diversified construction material, exists in two physical states--the first as a semifluid or plastic state while being mixed, transported and placed in final forms; the second as a solid after having set and cured. These features of concrete give it a wide application of use in coastal and waterfront structures under many special conditions. Ingredients for making concrete exist in virtually all areas of the world and the use of it in coastal structures depends only on the understanding and knowledge of the materials, design, and processes required for its end use. Concrete has proven to be an excellent construction material. The use of concrete is adaptable to many coastal structures. With good planning it will probably find many additional uses in the future to take advantage of its physical qualities.

Concrete can be considered to be made of two components, aggregates and paste. Aggregates are generally classified into two groups, fine and coarse. Fine aggregates consist of sand with particle sizes smaller than 6 millimeters (0.25 inch); coarse aggregates are those with particle sizes greater than 6 millimeters. Aggregates make up about 60 to 80 percent of the concrete. The paste is composed of cement, water, and sometimes admixtures and entrained air. Cement paste ordinarily constitutes 25 to 40 percent of total volume of concrete, cement being 7 to 15 percent and water 14 to 21 percent. Air and admixtures contents may range up to 8 percent.

Formulation of concrete in this manner was developed in Portland, England. Subsequently, the term Portland cement concrete has been used to describe cement concretes generally.

The durability of Portland cement concrete, defined as its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration, is a major factor in its excellence as a coastal construction material. Durable concrete will retain its original form, quality, and serviceability when exposed to its environment.

This section discusses the material used in making concrete, including additives that enhance its properties, the mixing of concrete, and the more important causes of concrete deterioration in coastal structures. It gives suggestions on how to prevent such damage, with particular attention to damage caused by freezing and thawing, aggressive chemical exposure, abrasion, reactive aggregates, and corrosion of embedded materials. Repair methods for concrete that has not withstood the forces of deterioration, and the use of protective coatings to enhance durability are also discussed.

2. Types of Portland Cement.

Portland cement types and characteristics for coastal structures are specified in ASTM Standards C150-78:

(a) Type I cement is used in ordinary structural concrete for foundations, roads, curbs, and ongrade foundations not subject to marine exposure or freezing and thawing conditions.

(b) Type IA is a normal air-entraining Portland cement for use in concrete structures, as mentioned for type I cement, subject to freezing climates.

(c) Type II cement is a mild sulphate-resisting cement and can be used for concrete in a marine environment not subject to freezing and thawing, if type V (listed below) is not available. However, type II cement concrete is not as durable in seawater as a type V cement concrete.

(d) Type IIA cement should be used for concrete in freezing atmospheres.

(e) Type III cement is used where a high early strength is needed. Concrete made with this cement will attain a strength in 7 days equivalent to that made with type I cement in 28 days. It should *not* be used for marine concrete.

(f) Type IIIA cement contains an air-entraining agent but otherwise is the same as type III.

(g) Type IV cement provides a low heat of hydration in concrete where a heat buildup may occur. It is used in structures such as dams, or in other mass concrete where such heat may be undesirable.

(h) Type V cement has a greater resistance to sulfates than all the others and should be used in all marine environments. It has a maximum tricalcium aluminate (C_3A) content of 5 percent. Addition of an air-entraining agent is mandatory in freezing climates.

(i) Low alkali cement. Federal specifications state that the summation of percentages of Na_2O plus 0.658 of the percentage of K_2O shall not exceed 0.6 percent of the total cement content. Low alkali cements are usually well below the 0.6-percent limit.

(j) For concrete piles used in soil containing from 0.10 to 0.20 percent water soluble sulfate (as SO_4) or used in water containing from 150 to 2 000 parts per million SO_4, the concrete should be made with cement containing not more than 8 percent tricalcium aluminate (C_3A) such as type II or a moderate sulfate-resistant (MS) cement. In environments where the water soluble sulfate exceeds 0.20 percent or the sulfate solution contains from 2 000 to 10 000 parts per million, Portland cement with the tricalcium aluminate content limited to 5 percent (e.g., type V) should be used. For very severe sulfate exposure (more than 10 000 parts per million), type V cement with a flyash admixture should be used.

(k) Where silica in the aggregates is reactive with alkali of the cement, a cement containing less than 0.60 percent alkali should be used. The foregoing alkalis if present in certain amounts may cause swelling of certain aggregates, such as opal or chalcedony. Such swelling can often be reduced by using low alkali cement.

There are many other cements used for special purposes, such as expansive cements, which cause the concrete to expand after setting (not used for marine concrete), waterproof Portland cement, plastic cement (used for making stucco and plaster), oil well cement, and special-blended custom and polymer cements.

3. Properties.

The basic properties of concrete are placeability, consistency, strength, durability and density. These properties will vary depending on the specific components and ratios of components added during mixing. Well-established relationships governing these properties are discussed below.

a. Placeability. Placeability (including satisfactory finishing properties) encompasses traits loosely accumulated in the terms "workability" and "consistency." Workability is considered to be that property of concrete which determines its capacity to be placed and consolidated properly and to be finished without harmful segregation. It is affected by the grading, particle shape, and proportions of aggregate, the amount of cement, the presence of entrained air, admixtures, and the consistency of the mixture. These factors are to be taken into account to achieve satisfactory placeability economically.

b. Consistency. Consistency, loosely defined, is the wetness of the concrete mixture. It is measured in terms of slump--e.g., the higher the slump the wetter the mixture--and it affects the ease with which the concrete will flow during placement. In properly proportioned concrete, the unit water content required to produce a given slump will depend on several factors. Water requirement increases as aggregates become more angular and rough textured (but this disadvantage may be offset by improvements in other characteristics such as bond to cement paste). Required mixing water decreases as the maximum size of the well-graded aggregate is increased. It also decreases with the entrainment of air. Mixing water requirement may often be significantly reduced by certain admixtures.

c. Strength. Strength is an important characteristic of concrete, but other characteristics such as durability, permeability, and wear resistance are often equally or more important. For a given set of materials and conditions, concrete strength is determined by the net quantity of water used per unit quantity of cement. The net water content excludes water absorbed by the aggregates. Differences in strength for a given water-cement ratio may result from changes in maximum size of aggregate; grading, surface texture, shape, strength, and stiffness of aggregate particles; differences in cement types and sources; air content; and the use of admixtures which affect the cement hydration process or develop cementitious properties themselves. However, in view of their number and complexity, accurate predictions of strength must be based on trial batches or experience with the materials to be used.

d. Durability. The ability of concrete to withstand environmental exposure is called durability. Concrete must be able to endure those exposures which may deprive it of its serviceability (e.g., freezing and thawing, wetting and drying, heating and cooling, chemicals, and deicing agents. Use of a low water-cement ratio will prolong the life of concrete

by reducing the penetration of aggressive liquids. Resistance to severe weathering, particularly freezing and thawing, and to salts used for ice removal is greatly improved by incorporation of a proper distribution of entrained air. Entrained air should be used in all exposed concrete in climates where freezing occurs. By using a suitable cement and a properly proportioned mix, concrete will resist sulfates in soil, ground water, or seawater, provided that concentrations are not in excess of 0.05 molar (7 grams) of Na_2SO_4 per liter of water. High-quality concrete will resist mild acid attack, but no concrete has good resistance to strong acids; special protection is necessary in this case.

Sometimes concrete surfaces will wear away as the result of abrasive action. In hydraulic structures, particles of sand or gravel in flowing water can erode surfaces. The use of high-quality concrete and, in extreme cases, a very hard aggregate may provide longer durability under these exposures. More detailed discussion of the exposures that impact durability of concrete and of the techniques to resist these impacts is discussed in subsection 6.

e. Density. For certain applications concrete may be used primarily for its weight characteristic. To the extent possible, selection of concrete proportions should be based on test data or experience with the materials actually to be used. Where such background is limited or not available, estimates given herein may be employed.

4. Components.

Concrete is composed principally of cement, aggregates, and water. It will contain some amount of entrapped air and may also contain purposely entrained air obtained by use of an admixture or air-entrained cement. Admixtures are also frequently used for other purposes such as to accelerate, retard, and improve workability, reduce mixing water requirement, and increase strength, durability, density, and appearance. The required characteristics are governed by the use to which the concrete will be put and by conditions expected to be encountered at the time of placement. These are often, but not always, reflected in specifications for the job.

a. Mixing Water For Concrete.

(1) General Requirements. Almost any natural water can be used as mixing water for making concrete. Potable freshwater is usually acceptable as satisfactory mixing water but should meet ASTM Standard C94. Water suitable for making concrete, however, may not be fit for drinking. Water high in chlorides should not be used in concrete containing steel reinforcement.

Water of questionable suitability can be used for making concrete if mortar cubes made with it have 7- and 28-day strengths equal to at least 90 percent of comparison specimens made with tapwater. Mortar cubes should be made and tested according to ASTM Standard C109. In addition, Vicat needle tests (ASTM Standard C191), should be made to ensure that impurities in the mixing water do not adversely shorten or extend the setting time of the cement. Excessive impurities in mixing water also may cause efflorescence, staining, or corrosion of reinforcement. Therefore, certain [illegible]

limits may be set on chlorides, sulfates, alkalies, and solids in the mixing water. A water source comparable in analysis to any of the waters in Table 5 is probably satisfactory for use in concrete.

Table 5. Chemical limits for mixing water.

Chemicals	Maximum concentration,[1] (ppm)	Test method[2]
Chloride, as CL		ASTM Std. D512
Prestressed concrete or concrete in bridge decks	500[3]	
Other reinforced concrete in moist environments or containing aluminum embedments or dissimilar metals or with stay-in-place galvanized metal forms	1 000[3]	
Sulfate, as SO_4	3 000	ASTM Std. D516
Alkalies, as (Na_2O + 0.658 K_2O)	600	
Total solids	50 000	AASHTO T26 (Sec. 3.1)

[1]Wash water reused as mixing water in concrete can exceed the listed concentrations of chloride and sulfate if it can be shown that the concentration calculated in the total mixing water, including mixing water on the aggregates and other sources, does not exceed the stated limits.

[2]Other test methods that have been demonstrated to yield comparable results can be used.

[3]For conditions allowing use of $CaCl_2$ accelerator as an admixture, the chloride limitation may be waived by the purchaser.

Water containing less than 2 000 parts per million of total dissolved solids can generally be used satisfactorily for making concrete. Water containing more than 2 000 parts per million of dissolved solids should be tested for its effect on strength and time of set. Water containing 2 000 to 3 000 parts per million, not including Na_2SO_4, of dissolved solids is acceptable if free of organic matter. American Concrete Institute (ACI) Committee 201 (1977), limits chloride ions to percentages of weight according to types of concrete (Table 6).

Water for use in prestressed work should be more definitely restricted in salt, silt, and organic contents. It should contain

Table 6. Permissible chloride ions.

Type of Concrete	Maximum (pct)
Prestressed concrete	0.06
Conventionally reinforced concrete in a moist environment and exposed to chloride	0.10
Aboveground building construction where concrete will stay dry (does not include locations where concrete will be occasionally wetted such as waterfront structures).	No limit for corrosion

(a) no impurities that will cause a change in time of set greater than 2.5 percent nor a reduction in 14-day strength greater than 5 percent as compared with distilled water;

(b) less than 650 parts per million of chloride ion (some authorities permit up to 1 000 parts per million);

(c) less than 1 300 parts per million of sulfate ion (some authorities limit this to 1 000 parts per million); and

(d) no oil.

Seawater may be used, if no other is available, and no steel reinforcement is present. The early strength of seawater concrete will be somewhat stronger than that made with freshwater but after about a month the strength of the freshwater concrete will be stronger. At the Port of Los Angeles, thousands of specimens were made for long-time testing using seawater for gaging and tapwater for control specimens. Storage environments were as follows: fog room for controls, air, freshwater and seawater. Compression tests were made at increments of 1 day, 7 days, 28 days, 6 months, 1 year, and thereafter each 5 years through 35 years.

The results showed that in the early phases of the program (within the first year) strength gains for the seawater-gaged concrete (compressive strength, modulus of rupture, and modulus of elasticity) slightly exceeded those of the tapwater controls. However, beginning at about 1 year, the tapwater control increased above that of the seawater specimens. At the end of the 35-year period the tapwater series were roughly 15 percent stronger then the seawater series. All concrete mixes were of excellent quality, structural grade concrete and, of course, no form of reinforcement was used. Table 7 compares tapwater to seawater for total dissolved solids.

Seawater containing up to 35 000 parts per million of dissolved salts is generally suitable as mixing water for unreinforced concrete. The strength reduction can be compensated for by reducing the water-cement ratio. Quality concrete can be made with seawater if the mix is properly adjusted.

Table 7. Typical analyses of city water supplies and seawater.

Dissolved Solids	In tapwater (analysis no.)						In seawater[1]
	1	2	3	4 (ppm)	5	6	
Silica (SiO_2)	2.4	0.0	6.5	9.4	22.0	3.0	-
Iron (Fe)	0.1	0.0	0.0	0.2	0.0	0.0	-
Calcium (Ca)	5.8	15.3	29.5	96.0	3.0	1.3	50-480
Magnesium (Mg)	1.4	5.5	7.6	27.0	2.4	0.3	260-1 410
Sodium (Na)	1.7	16.1	2.3	183.0	215.0	1.4	2 190-12 200
Potassium (K)	0.7	0.0	1.6	18.0	9.8	0.2	70-550
Bicarbonate (HCO_3)	14.07	35.8	122.0	334.0	549.0	4.1	-
Sulfate (SO_4)	9.7	59.9	5.3	121.0	11.0	2.6	580-2 810
Chloride (Cl)	2.0	3.0	1.4	280.0	22.0	1.0	3 960-20 000
Nitrate (NO_3)	0.5	0.0	1.6	0.2	0.5	0.0	-
Total dissolved solids	31.0	250.0	125.0	983.0	564.0	19.0	35 000

[1]Different seas contain different amounts of dissolved salts.

When suitable freshwater is not available, seawater can also be used for making reinforced concrete. Its use may increase the risk of corrosion, but the risk is reduced if the reinforcement has sufficient cover and if the concrete is watertight and contains an adequate amount of entrained air. Reinforced concrete structures made with seawater and exposed to marine environment should have a water-cement ratio of less than 0.45 and the reinforcement cover should be at least 75 millimeters (3 inches). Seawater should not be used to make prestressed concrete in which the prestressing steel is in contact with the concrete. Sodium or potassium salts present in seawater used for mix water can produce substances that combine with alkali-reactive aggregates in the same manner as when combined with cement alkalies. Therefore, seawater should not be used as mixing water for concrete with known potentially alkali-reactive aggregates, even when the alkali content of the cement is low.

(3) Impurities. The following resume discusses the effects of certain impurities in mixing water on the quality of plain concrete.

(a) Alkali Carbonate and Bicarbonate. Sodium carbonate can cause very rapid setting, bicarbonate can either accelerate or retard set. In large concentrations the salts can materially reduce concrete strengths. When the sum of these disolved salts exceeds 1 000 parts per million, tests for their setting time and 28-day strength should be made.

(b) Chloride and Sulfate. Concern over a high cloride content in the water is chiefly due to the possible adverse effect of chloride ions on the corrosion of reinforcing steel or prestressing strands. The chloride level at which corrosion begins is about 7.6 newtons per cubic meter (1.3 pounds per cubic yard). Placing an acceptable limit on chloride content for any one ingredient, such as mixing water, is difficult considering the several sources of chloride ions in concrete. An acceptable limit

in the mixing water depends upon how significantly mixing water contributes to the total chloride content. Suggested limits are shown in Table 5. Water containing less than 500 parts per million of chloride ion generally is considered acceptable. However, the contribution of chlorides from other ingredients also should be considered.

(c) Iron Salts. Iron salts in concentrations up to 40 000 parts per million do not usually affect mortar strengths adversely.

(d) Miscellaneous Inorganic Salts. Salts of manganese, tin, zinc, copper, and lead in mixing water can cause a significant reduction in strength and large variations in setting time. Of these, salts of zinc, copper, and lead are the most active. Other salts that are especially active as retarders include sodium iodate, sodium phosphate, sodium arsenate, and sodium borate. All can greatly retard both set and strength development when present in concentrations of a few tenths percent by weight of the cement. Generally, concentrations of these salts up to 500 parts per million can be tolerated in mixing water.

Another salt that may be detrimental to concrete is sodium sulfide; even the presence of 100 parts per million warrants testing.

(e) Acid Waters. Generally, mixing waters combining hydrochloric, sulfuric, and other common inorganic acids in concentrations as high as 10 000 parts per million have no adverse effect on concrete strength. Acid waters with pH less that 3.0 may create handling problems and should be avoided.

(f) Algae. Water containing algae is unsuited for making concrete because the algae can cause excessive reduction in strength either by influencing cement hydration or by causing a large amount of air to be entrained in the concrete. Algae may also be present on aggregates, in which case the bond between the aggregate and cement paste is reduced.

b. Polymers in Concrete.

(1) General. The following three types of concrete materials utilize polymers to form composites: (1) polymer-impregnated concrete (PIC), which is a hydrated Portland cement concrete that has been impregnated with a monomer and subsequently polymerized in situ; (2) polymer-Portland cement-concrete (PPCC), which is produced by adding either a monomer or polymer to a fresh concrete mixture and subsequently curing and polymerizing the material in place; and (3) polymer concrete (PC), which is a composite material formed by polymerizing a monomer and aggregate mixture.

A monomer is an organic molecular species which is capable of combining chemically with molecules of the same or other species to form a high molecular weight material known as a polymer. A polymer consists of repeating units derived from the monomers which are linked together in a chainlike structure. The chemical process through which these linkages occur is known as polymerization.

(2) Polymer-Impregnated Concrete. The selection of suitable monomers for polymer-impregnated concrete (PIC) is based on the impregna-

tion and polymerization characteristics, availability and cost, and the properties of the resultant polymer and PIC. Liquid vinyl monomer systems have generally been used. Monomers are normally supplied containing an inhibitor to prevent premature polymerization of the monomer. Since polymerization begins immediately on adding a promoter, its use in PIC would be restricted to shallow impregnations.

The basic method of producing polymer-impregnated concrete (PIC) consists of the fabrication of precast concrete specimens, ovendrying, saturation with monomer, and in-situ polymerization.

For full impregnation, good-quality concrete having a cross section of up to 305 millimeters (12 inches) will require soaking in monomer for about 60 minutes under a pressure of 69 kilopascals (10 pounds per square inch). Concrete may be only partially impregnated when improved strength is not needed but greater durability is desired.

(3) Polymer-Portland Cement-Concrete. Polymer-Portland cement-concrete (PPCC) has been prepared with both premixed and postmixed polymerized materials. The premixed polymerized materials include latexes and polymer solutions or dispersions. The postmix polymerized PPCC has been made with a number of resins and monomers.

(a) Polymer Latexes. At present, latex-modified concretes represent the large majority of commerical applications of polymer-modified concretes in the United States. Suitable latex formulations greatly improve the shear bond, tensile, and flexural strength of cements and mortars.

(b) Polymer Solutions. Thermosetting water-soluble polymers which have been added to fresh concrete include epoxies, amino-resins, polyesters, and formaldehyde derivatives. Thermoplastic materials include polyvinyl alcohol and polyacrylamides.

PPCC process technology is based upon overcoming the incompatibilities of most organic polymers and their monomers with mixtures of Portland cement, water, and aggregate. The mix proportioning of latex PPCC will vary in much the same way as do normal concretes and mortars.

(4) Polymer Concrete. Most of the work on polymer concrete (PC) has been with polyester styrene resin systems, and to a lesser extent with furan, epoxy, and vinylester resins systems. The polyester resins are attractive because of moderate cost, availability of a great variety of formulations, and moderately good PC properties.

Most of the monomer and resin systems for PC are polymerized at ambient temperatures. Vinyl monomer systems can be polymerized with catalysts such as benzoyl peroxide with an amine promoter. The polyester-styrene systems are polymerized with promoter-catalyst systems such as methylethyl ketone peroxide with cobalt napthanate promoter. Other systems include amine curing agents for epoxy resins.

Mixing and placing techniques for PC are based on adaptation of existing equipment and methods for producing Portland cement concrete. A knowledge

of polymer chemistry is helpful, but not essential; directions for curing mixes are available from the resin manufacturers. Curing of PC may be performed by thermal catalytic, promoter-catalysts or radiation techniques. Promoter-catalyst systems are frequently best suited for PC, with curing times varied, as needed, between a few minutes and several hours. Full strength is attained when polymerization is completed. PC has been made with epoxy, polyester, and furan resins, and more recently with sytrene monomer systems.

c. Aggregates.

(1) Normal Aggregates. Normal aggregates consist of clean sand, river-washed gravel, and crushed rock. In certain locations volcanic rock, such as basalt, may be used. They should have clean, hard and uncoated particles and comply with ASTM Standard C33. Other ASTM tests for concrete aggregates are shown in Table 8.

Harmful substances may be present in aggregates. These include organic matter, rubbish of all kinds, silt, clay, coal, lignite, dolomitic limestones, chalcedonic cherts, opal, cristobalite, some types of volcanic glass, and pyrites. An aggregate containing these substances may be considered as reactive. Materials finer than the No. 200 sieve may form coatings on the aggregates which weaken the bond between the aggregate and the cement paste. Soft particles of aggregate affect the wear resistance and durability of the concrete.

Tests used to qualify aggregates to be used to make durable concrete are as follows:

(a) Abrasion resistance tests;

(b) sulfate soundness tests (used for many years as an index of quality, however, experience has shown that it does not correlate well with the actual performance of aggregates in concrete);

(c) tests for organic impurities (on aggregates from new sources);

(d) laboratory freezing and thawing tests (of limited value, but do furnish useful information for new source material); and

(e) tests to determine presence of opal and chalcedony (on aggregates from new sources) by making mortar bars and testing them according to ASTM Standard C342

It is an interesting fact that the water requirement of a given consistency for concrete decreases in inverse proportion to the maximum size of the coarse aggregate. For example, a 19-millimeter (0.75 inch) size coarse aggregate would require about 1.49 kilonewtons (335 pounds) of water, per 0.76 cubic meter (1 cubic yard) of concrete; a 50.8-millimeter (2 inch) aggregate would only need about 1.22 kilonewtons (275 pounds) per 0.76 cubic meter (1 cubic yard). The latter would lower the water-cement

Table 8. Characteristics and tests of aggregates.

Characteristic	Significance	ASTM Standard	Requirement of item reported
Resistance to abrasion	Index of aggregate quality; wear resistance of floor pavements	C131 C295 C535	Maximum percentage of weight loss
Resistance to freezing and thawing	Surface scaling, roughness, loss of section, and unsightliness	C295 C666 C682	Maximum number cycles or period of frost immunity; durability factor
Resistance to disintegration by sulfates	Resistance to weathering action	C88	Weight loss, particles exhibiting distress
Particle shape and surface texture	Workability of fresh concrete	C295 D3398	Maximum percentage of flat and elongated pieces
Grading	Workability of fresh concrete; economy	C117 C136	Minimum and maximum percent passing standard sieves
Bulk unit weight or density	Mix design calculations; classifications	C29	Compact weight and loose weight
Specific gravity	Mix design calculations	C127, fine aggregate C128, coarse aggregate C29, slag	-
Absorption and surface moisture	Control of concrete quality	C70 C127 C128 C566	
Compressive and flexural strength	Acceptability of fine aggregate failing other tests	C39 C78	Strength to exceed 95 percent of strength achieved with purified sand
Definitions of constituents	Clear understanding and communications	C125 C294	-

ratio and, of course, produce concrete of a greater strength than that containing the 19-millimeter aggregate. Table 9 shows maximum aggregate sizes for various uses.

Table 9. Maximum size of aggregate recommended for various types of construction.

Section	Use or Features	Aggregate Size (mm)	(in)
≤190.5 mm wide	heavily reinforced floor and roof slabs; parapets, cobels and where space is limited	19	0.75
>190.5 mm wide with clear distance between reinforcement bars ≥ 57 mm		38.1	1.5
>305 mm wide unreinforced sections and >457 mm wide reinforced sections with clear distance between reinforcement bars >114.3 mm but < 229 mm	Piers, walls, baffles and stilling basin floor slabs in which satisfactory placement of 152.4 mm or cobble concrete cannot be accomplished even though reinforcement spacing would permit the use of larger aggregates.	76.2	3
Massive sections with clear distance between reinforcing bars ≥ 229 mm	Retaining walls, piers and baffles; in which suitable provision is made for placing concrete containing the larger size aggregate without producing rock pockets or other undesirable results.	152.4	6

Gap-graded aggregates can often be used effectively in areas where ASTM C33 standards cannot be met. A typical gap-graded aggregate may contain only one size of coarse aggregate together with sand. In this respect, the resultant concrete would resemble that made with prepacked concrete.

When natural aggregates are found to be unacceptable through service records or tests, they may sometimes be improved by removing lightweight, soft, or otherwise inferior particles by processing.

(2) Lightweight Aggregate. There are a number of materials used to produce lightweight concrete. Among the natural aggregates are: tuff,

pumice, volcanic cinders, scoria, and diatomite rocks. Pumice is frequently used in structural concrete. For example, parts of the large concrete counterweights on a bascule bridge (Fig. 15), were composed of normal structural concrete (weight about 23.6 kilonewtons per cubic meter or 150 pounds per cubic foot), lightweight pumice concrete of 15.4 kilonewtons per cubic meter (98 pounds per cubic foot), and heavyweight concrete of 35.3 kilonewtons per cubic meter (225 pounds per cubic foot). Concrete made with pumice weighs from 14.1 to 15.7 kilonewtons per cubic meter (90 to 100 pounds per cubic foot).

In the artificial lightweight aggregate family is perlite. This produces a poor grade of concrete weighing from 7.9 to 12.6 kilonewtons per cubic meter (50 to 80 pounds per cubic foot), which is often used as an underlayer for built-up roof decks. It will not produce structural grade concrete. Expanded clay aggregates produce a lightweight, structural quality concrete with densities ranging from 14.1 to 17.3 kilonewtons per cubic meter. Although there are other manufactured lightweight aggregates for making concrete, this report will conclude with vermiculite. Concrete made with the vermiculite (not used for structural concrete) is used extensively as an insulating material and weighs from 5.5 to 11.8 kilonewtons per cubic meter (35 to 75 pounds per cubic foot).

(3) Heavy Aggregate. Heavyweight concrete is made with normal coarse aggregates (ASTM Standard C33) and heavy natural or manufactured aggregates such as magnetite (specific gravity 4.2 to 4.4), limonite (specific gravity 5.0 to 5.5), and barite (specific gravity 2.5 to 3.5). Some of these minerals could contain pyrite, which can decompose on weathering, and should not be used in concrete. Magnetite and limonite should be tested for the presence of pyrite before using in concrete.

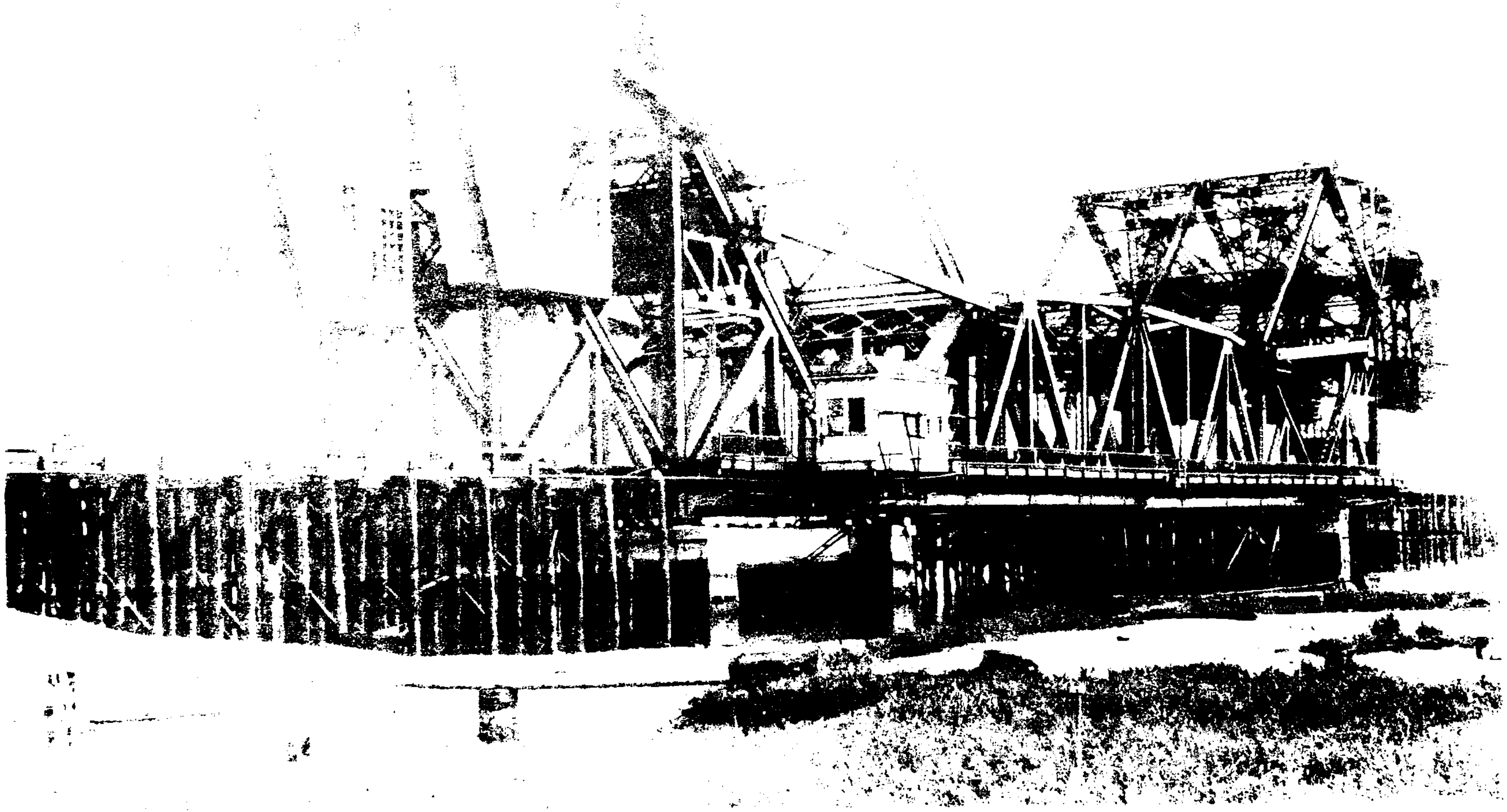
Manufactured heavy aggregates are usually iron and steel products. Concrete from these products can reach more than 47.1 kilonewtons per cubic meter (300 pounds per cubic foot). More information on heavy aggregates is provided in "Design and Control of Concrete Mixtures" (Portland Cement Association, 1979).

(4) Regional Aggregates. For the sake of economy, it may be desireable to use aggregates from the nearest source, unless they contain harmful minerals such as pyrite or chalcedony, even if they do not fully meet with the requirements of ASTM Standard C33. If it is essential to use aggregates containing reactive minerals, pozzolon admixtures are added to reduce or eliminate potential expansion from alkali reactive aggregates.

(5) Coral. Coral deposits are found in many oceans of the world. When mined and prepared for use as an aggregate for making concrete, the physical and chemical properties of coral may vary widely. When coral aggregates are used to produce structural concrete, a strength factor is established by using trial mixes until the proper strength has been attained. Cores were taken in 1972 from coral aggregate concrete (made by the Japanese many years prior to 1941), on the island of Kwajalein. The average compressive strength of the cores was 13.8 kilopascals (2 000 pounds per square inch).

(6) Chemical Reactions of Aggregates.

(a) Types of Reactions. Chemical reactions of aggregates in concrete can affect the performance of concrete. Some reactions may be



... [illegible] weight concrete counter balances.

beneficial, but others result in serious damage to the concrete by causing abnormal expansion, cracking, and loss of strength (Woods, 1968). The reaction that has received greatest attention and was the first to be recognized involves a reaction between alkalies (Na_2O and K_2O), from the cement or from other sources with hydroxyl, and certain siliceous constituents that may be present in the aggregate. This phenomenon was originally, and is still sometimes, referred to as "alkali-aggregate reaction," but in recent years it has been more properly designated as "alkali-silica reaction."

Deterioration of concrete has occurred in certain sand-gravel aggregates. The deterioration has been regarded as a chemical phenomenon and is a reaction between the alkalies in cement and some siliceous constituents of the aggregates, complicated by environmental conditions that produce high concrete shrinkage and concentration by drying (Hadley, 1968). It has also been clearly demonstrated that certain carbonate rocks participate in reactions with alkalies that, in some instances, produce detrimental expansion and cracking. Detrimental reactions are usually associated with argillaceous dolomitic limestones which have somewhat unusual textural characteristics (Hadley, 1964). This reaction is designated as "expansive alkali-carbonate reaction."

Other damaging chemical reactions involving aggregates include the oxidation or hydration of certain unstable mineral oxides, sulfates, or sulfides that occur after the aggregate is incorporated in the concrete e.g., the hydration of anhydrous magnesium oxide, calcium oxide, or calcium sulfate, or the oxidation of pyrite) (Mielenz, 1964). Still other reactions may result from organic impurities (such as humus and sugar). Engineers should be aware of these possibilities and supply corrective measures where necessary. Careful testing and examination of the aggregates will usually indicate the presence of such reactive impurities and their use in concrete can be avoided. The alkali-silica, cement-aggregate, and expansive carbonate reactions are most important.

(b) The Alkali-Silica Reaction. This reaction can cause expansion and severe cracking of concrete structures and pavements. The phenomenon is complex, and various theories have been advanced to explain field and laboratory evidence (Diamond, 1976). Unanswered questions remain. Apparently, reactive material in the presence of potassium, sodium, and calcium hydroxide derived from the cement reacts to form either a solid nonexpansive calcium-alkali-silica complex or an alkali-silica complex (also solid) which can expand by imbibition of water.

1 Laboratory Tests for Alkali-Silica Reactivity. Laboratory tests should be made on aggregates from new sources and when service records indicate that reactivity may be possible. The most useful are:

(a) Petrographic examination (ASTM Standard C295),

(b) mortar bar test for potential reactivity (ASTM Standard C227), and

(c) chemical test for potential reactivity (ASTM Standard 289).

a Petrographic Examination. Petrographic examination provides a recommended practice for the petrographic examination of aggregates. Recommendations are available which show the amounts of reactive minerals that can be tolerated. The reactive rocks and minerals that have been more frequently encountered since 1960 appear to have larger potassium proportions and are harder to recognize in petrographic examination. Highly deformed quartz with an angle of undulatory extinction of 35° to 50° or more and with deformation lamellae appear characteristic of the reactive quartz-bearing rocks. Relatively coarse-grained micas have also been regarded as reactive constituents; fine-grained micas are reactive in argillites (Dolar-Mantuani, 1969).

b Mortar Bar Test for Potential Reactivity. This test is the method most generally relied on to indicate potential alkali reactivity. Acceptance criteria are given by ASTM Standard C33 for evaluating these test results. The procedure is useful not only for the evaluation of aggregates, but also for the evaluation of specific aggregate-cement combinations. However, criteria have not been developed for the metamorphic siliceous and silicate rocks.

c Chemical Test for Potential Reactivity. This test is the method used primarily for a quick evaluation of natural aggregates. The results are obtainable in a few days as compared with 3 to 6 months or more with the mortar bar test. Acceptance criteria for this test are given in ASTM Standard C33. Care must be exercised in interpreting the results of this test. This test method has given questionable results when evaluating lightweight aggregates; therefore, it is not recommended for this purpose (Ledbetter, 1973).

2 General Criteria for Judging Reactivity. When available, the field performance record of a particular aggregate, if it has been used with cement of high alkali content, is the best means for judging its reactivity. If such records are not available, the most reliable criteria are petrographic examination with corroborating evidence from the mortar bar test (U.S. Army, Corps of Engineers, 1971c), sometimes supplemented by tests on concrete although these have not been standardized. The chemical test results should also be used in conjunction with results of the petrographic examination and mortar bar test. It is preferable not to rely on the results of only one kind of test in any evaluation (U.S. Army, Corps of Engineers, 1971c).

3 Recommended Procedures with Alkali-Reactive Aggregates. If aggregates are shown by service records or laboratory examination to be potentially reactive, they should not be used when the concrete is to be exposed to seawater or alkali environments if nonreactive aggregates are available (Highway Research Board, 1958). When reactive aggregates must be used, this should be done only after thorough testing, and preferably after service records have established that, with appropriate limits on the alkali content of the cement, or with the use of appropriate amounts of an effective pozzolan, or both, satisfactory service can be anticipated. In cases where seawater or alkaline soil environments are not involved, and there are no sound materials available economically, reactive materials may be used provided certain limits are set in the specifications:

(a) Specify a low alkali cement having a maximum of 0.6 percent equivalent Na_2O.

(b) prohibit the use of seawater or alkali soil water as mixing water;

(c) avoid addition of sodium or potassium chloride; and

(d) where low alkali cements are not economically available, use a suitable pozzolanic material as prescribed by ASTM Standard C618 and tested in accordance with ASTM Standard C441 (to determine their effectiveness in preventing excessive expansion due to the alkali-aggregate reaction).

Whenever the use of pozzolanic materials is considered, it should be remembered that if these materials increase water demand, they may cause increased drying shrinkage in concrete exposed to drying. Increased water demand results from high fineness and poor particle shape. The rate of strength development in correctly proportioned pozzolanic concrete can equal that of Portland cement concretes, i.e., 28 days.

(c) Cement-Aggregate Reaction. Recent research indicates that the cement-aggregate reaction is mainly a reaction between the alkalies in the cement that produce high pH and abundant hydroxyl and siliceous constituents of the aggregates. However, the field performance of concretes made with reactive sand and gravels does not correlate well with cement alkali content. The concrete deterioration results from moderate interior expansion caused by alkali-silica reactivity, and surface shrinkage caused by severe drying conditions. Evaporation at the surface of the concrete causes an increase in alkali concentration in the pore fluids near the drying surface, and a net migration of alkali toward this surface. Under these conditions even a low alkali cement may cause objectionable deterioration, particularly near the surface. This alkali distribution is altered by the leaching of alkalies near the surface during periods of heavy rain (Hadley, 1968).

1 Identification by Laboratory Tests. Although special tests, such as ASTM Standard C342, have been devised to indicate potential damage from this phenomenon, their reliability is doubtful.

2 Recommended Procedure to be Employed with Potentially Deleterious Cement-Aggregate Combinations. The use of potentially deleterious cement-aggregate combinations should be avoided where possible. However, if they must be used, a suitable pozzolan that does not increase drying shrinkage and 30 percent or more (by weight) of coarse limestone should be used with potentially deleterious cement-aggregate combinations. Concrete tests should be used to determine whether the resulting combination is satisfactory.

(d) Expansive Alkali-Carbonate Reactivity. Certain limestone aggregates, usually dolomitic, have been reported as reactive in concrete structures. There are many unanswered questions, and more than one mechanism has been proposed to explain expansive carbonate reactivity. The affected concrete is characterized by a network of pattern or map cracks

usually most strongly developed in areas of the structure where the concrete has a constantly renewable supply of moisture, such as close to the waterline in piers, from the ground behind retaining walls, beneath road or sidewalk slabs, or by wick action in posts or columns. A distinguishing feature from alkali-silica reaction is the general absence of silica gel exudations at cracks. Additional signs of the severity of the reaction are closed expansion joints with possible crushing of the adjacent concrete (Hadley, 1964).

1 Identification by Laboratory Tests. The most useful laboratory tests are discussed below.

a Petrographic Examination. This examination of aggregates may be used to identify the features of the rock. The presence of all or any dolomite in a fine-grained carbonate rock makes it desirable to perform the rock cylinder test (ASTM Standard C586). This is recommended whether or not the texture is believed to be typical, and whether or not insoluble residue including clay amounts to a substantial part of the aggregate. As expansive rocks are recognized from more areas, the more variable the textures and compositions appear to be.

b Expansion of Concrete Prisms Test. This test is performed with prisms made of job materials and stored at 100 percent relative humidity at 23^{o} Celsius, (73^{o} Farenheit), or (in order to accelerate the reaction) the prisms may be made with additional alkali and stored at elevated temperature. The comparison is usually made with the expansion of prisms containing a nonreactive control aggregate.

c Petrographic Analysis. A petrographic analysis of the concrete can confirm the type of aggregate present and its characteristics. Distress that has occurred in the aggregate and surrounding matrix, such as microcracking and macrocracking, may be observed. Reaction rims, which do not necessarily signify harmful results, may be observed in certain aggregate particles and may be identified as negative or positive by acid etching. Secondary deposits of calcium carbonate, calcium hydroxide, and ettringite (calcium sulfoaluminate) may be found in voids within the concrete; however, there are no deposits of silica, hardened or in gel form, associated with the suspect aggregate pieces.

d Other Laboratory Tests. Additional tests on alkali-carbonate reaction include identifying by visual observation sawed or ground surfaces. X-ray examination of reaction products is also sometimes useful.

e Criteria for Judging Reactivity. Several criteria are available for judging the reactivity of aggregates. These include definitive correlations between expansions occurring in the laboratory in rock cylinders or concrete prisms and deleterious field performance which have not yet been established. The factors involved are complex and include the heterogeneity of the rock, coarse aggregate size, permeability of the concrete, and seasonal changes in environmental conditions in service, principally availability of moisture, level of temperature, and possibly the use of sodium chloride as a deicing chemical.

It is not certain that rapid determination of potential reactivity can always be made by using the rock cylinder test, because some rocks showing an initial contraction may develop considerable expansion later on. Expansions greater than 0.10 percent in the rock cylinders are usually taken as a warning that further tests should be undertaken to determine expansion of the aggregate in concrete. Fortunately, many carbonate rocks that expand in rock cylinders do not expand in concrete.

2 Recommended Procedures to Minimize Alkali-Carbonate Reactivity. Procedures that can be employed to mitigate the effects of the reaction include:

(a) Avoiding reactive rocks by selective quarrying;

(b) dilution with nonreactive aggregates, or use of a smaller maximum size; and

(c) use of low alkali cement (probably 0.4 percent combined alkali or lower), which will prevent harmful expansions in most cases; however, in pavements where sodium chloride is used as a deicing chemical, this cannot be taken as certain.

Of these measures, the first is the safest and usually the most economical.

(e) Preservation of Concrete Containing Reactive Aggregate. There are no known methods of adequately preserving existing concrete which contains the elements that contribute to the previously described chemical reactions. Water or moisture is partly involved in at least two of these reactions. The destructive effects of freezing and thawing are more pronounced after the initial stages of destruction by these chemical reactions. Therefore, any practicable means of decreasing the exposure of such concrete to water may extend its useful life.

d. Admixtures.

(1) General. An admixture is defined as a material other than water, aggregates, and hydraulic cement, that is used as an ingredient of concrete or mortar and is added to the batch immediately before or during its mixing. ASTM Standard C494 classifies certain chemical admixtures in terms of function as follows:

(a) Type A, water-reducing admixtures,

(b) Type B, retarding admixtures,

(c) Type C, accelerating admixtures,

(d) Type D, water-reducing and retarding admixtures, and

(e) Type E, water-reducing and accelerating admixtures.

These admixtures are discussed according to the type of materials consituting the admixture or to the characteristic effects of their use.

(2) Water-Reducing and Retarding Admixtures. Water-reducing admixtures are used to improve the quality of concrete, to obtain specified strength at lower cement content, or to increase the slump of a given mixture without increase in water content. They also may improve the properties of concrete containing aggregates that are harsh or poorly graded, or both, or may be used in concrete that must be placed under difficult conditions. Set-retarding admixtures delay the onset of hardening, prolonging the period when the concrete is workable. Both types of admixtures are useful when placing concrete by means of a pump or when using a tremie process. The materials that are generally available for use as water-reducing admixtures and set-retarding admixtures fall into four general classes:

(a) Lignosulfonic acids and their salts;

(b) modifications and derivatives of lignosulfonic acids and their salts;

(c) hydroxylated carboxylic acids and their salts; and

(d) modifications and derivatives of hydroxylated carboxylic acids and their salts.

Hydroxylated carboxylic acid salts act as water-reducing, nonair-entraining retarders. Lignosulfonates are available as the calcium, sodium or ammonium salts. Admixtures of classes (a) and (c) can be used either alone or combined with other organic or inorganic, active or essentially inert substances. They are water-reducing, set-retarding admixtures.

Admixtures of classes (b) and (d) are water-reducing admixtures offered as combinations of substances designed either to have no substantial effect on rate of hardening or to achieve varying degrees of acceleration or retardation in rate of hardening of concrete; these admixtures may include an air-entraining agent.

The composition of the Portland cement affects the air-entraining properties of lignosulfonate admixtures in concrete. Concrete containing a lignosulfonate retarder generally requires 5 to 10 percent less water than comparable concrete without the admixture. Compressive strengths at 2 or 3 days are usually equal to or higher than those of corresponding concrete without the admixture and the strength at 28 days or later may be 10 to 20 percent higher.

Lignosulfonic acid salts, carboxylic acid salts, or modifications or derivatives thereof can be mixed or reacted with other chemicals that entrain air, modify setting time, or affect the strength development of concrete. Calcium chloride, neutralized wood resins, alkyl aryl sulfonates, and triethanolamine are examples of additives that have been used. The use of compounded or modified water reducers usually causes a water reduction of 5 to 10 percent at equal air content. Compressive strengths at ages greater than 2 days are usually from 10 to 20 percent higher than those of similar concretes without admixture.

(3) Accelerating Admixtures. Accelerating admixtures are added to concrete either (a) to increase the rate of early strength development, (b) to shorten the time of setting, or (c) for both purposes. Chemicals which

accelerate the hardening of mixtures of Portland cement and water include some of the soluble chlorides, carbonates, silicates, fluosilicates, and hydroxides (Steinour, 1960), and also some organic compounds such as triethanolamine (Newman, et al., 1943). Calcium aluminate cements and finely ground hydrated Portland cement have also been advocated.

Some of the soluble chlorides, particularly calcium chloride (Highway Research Board, 1952) and to a much lesser extent triethanolamine, have general applicability as admixtures in concrete. Some of the other materials are suitable only for use in the preparation of quick-set cements.

By far the best known and most widely used accelerator is calcium chloride. Many other materials have been found to accelerate the strength gain of concrete but, in general, they are seldom used, and only limited information concerning their effect on the properties of concrete is available. Most of the information given on accelerators applies mainly to the use of calcium chloride. The effects of accelerators on some of the properties of concrete are as follows:

(a) The setting time, initial and final, is reduced. The amount of reduction varies with the amount of accelerator used, the temperature of the concrete, and the ambient temperature. Excessive amounts of the accelerator may cause rapid setting.

(b) Less air-entraining admixture is required to produce the required air content. However, in some cases larger bubble sizes and higher spacing factors are obtained.

(c) Earlier heat release is obtained but there is no appreciable effect on the total heat of hydration.

(d) Compressive strength is increased substantially at early ages. The ultimate strength may be reduced slightly. The increase in flexural strength is usually less than that of the compressive strength.

(e) It is generally considered that the volume change is increased for both moist curing and drying conditions. There is a question of the degree of the effect caused by the accelerators as opposed to other factors influencing volume change.

(f) The resistance to freezing and thawing and to scaling caused by the use of deicing salts is increased at early ages, but may be decreased at later ages.

(g) The resistance to sulfate attack is decreased.

(h) The expansion produced by alkali-aggregate reaction is greater. This can easily be controlled by the use of low alkali cement or pozzolans.

(i) Corrosion of metals may occur, especially in the use of calcium chloride when steam curing is employed. The use of calcium chloride in recommended amounts does not cause progressive corrosion

of conventional steel reinforcement in typical reinforced concrete under normal conditions where the bars have sufficient concrete cover. Stannous chloride when properly used acts as an accelerator and does not cause corrosion of the steel even when steam curing is used.

(4) Calcium Chloride. Calcium chloride is available in two forms. Regular flake calcium chloride, ASTM Standard D98 (type 1), contains a minimum of 77 percent $CaCl_2$. Concentrated flake, pellet, or granular calcium chloride ASTM Standard D98 (type 2) contains a minimum of 94 percent of $CaCl_2$. Calcium chloride can generally be used safely in amounts up to 2 percent by weight of the cement (McCall and Claus, 1953). Larger amounts may be detrimental and, except in rare instances, provide little additional advantage. The benefits of the use of calcium chloride are usually more pronouned when it is employed in concrete with a mixing and curing temperature below 21° Celsius (70° Farenheit). At high mixing and curing temperatures long-term strength, especially flexural strength, may decrease, and shrinkage and cracking may increase.

Laboratory tests have indicated that most increases of compressive strengths of concrete resulting from the use of 2 percent of calcium chloride by weight of cement are in the range of 2 760 to 6 890 kilopascals (400 to 1 000 pounds per square inch) at 1 to 7 days for 21° Celsius curing. At 4.4° Celsius (40° Farenheit) curing the increases in strengths obtained at 1 and 7 days with calcium chloride are in the same range as that for 21° Celsius curing. The increase in strength usually reaches its maximum in 1 to 3 days and thereafter generally decreases. At 1 year, some increase is still evident in concrete made with most cements. The specific effect of the use of calcium chloride varies, however, for different cements as is indicated by the range of strength increases cited above for the early ages.

The relative increase in flexural strength of concrete resulting from the use of 1 or 2 percent of calcium chloride is not as great as the increase in compressive strength. Calcium chloride increases the flexural strength at 1 and 3 days, but decreases the flexural strength at 28 days or at later ages (McCall and Claus, 1953).

Flexural strengths of concretes containing 1 to 2 percent calcium chloride are usually increased over the strengths of similar concrete without the admixture by 40 to 90 percent at 1 day and by 5 to 35 percent at 3 days, respectively, when moist cured at 21° Celsius. At 28 days, decreases of up to 12 percent have been reported from laboratory tests of moist-cured concrete.

The use of 1 percent calcium chloride by weight of the cement is sufficient in most cases to accelerate setting and increase strength sufficiently for cold weather concreting, with the understanding that cold weather protection is provided. The selection of the optimum amount should be based on the type of cement, the temperature of the concrete, and the ambient air temperature.

Calcium chloride may promote corrosion of the usual reinforcement in concrete even though adequate concrete cover is provided for the steel.

However, it should not be used where stray electric currents are expected and should not be used in prestressed concrete because of possible stress corrosion of the prestressing steel (Arber and Vivian, 1961). Calcium chloride in concrete may be expected to aggravate corrosion of embedded galvanized metal and of galvanized forms that are left in place. Combinations of metals, such as aluminum-alloy electrical conduit and steel reinforcing, should not be used in concrete exposed to water.

Calcium chloride may be especially beneficial for concrete exposed to low or freezing temperatures at early ages if used as recommended in the ACI Standard ACI 604-56. Calcium chloride increases the rate of early heat development and accelerates the set, but lowers the freezing point of the water in concrete only to an insignificant extent.

(5) Air-Entraining Admixtures. Many materials, including natural wood resins, fats, and oils, may be used in preparing air-entraining admixtures. These materials are usually insoluble in water and generally must be chemically processed before they can be used as admixtures. Since not all such materials produce a desirable air-void system, air-entraining admixtures should meet the requirements of the ASTM Standard C260.

Air-entrained concrete containing a large number of very small air bubbles is several-fold more resistant to frost action than nonair-entrained concrete made of the same materials. Air-entrained concrete should be a dense, impermeable mixture that is well-placed, protected, finished, and cured if maximum durability is to be obtained.

Air entrainment, while improving both workability and durability, may reduce strength. Within the range of air content normally used, the decrease in strength usually is about proportional to the amount of air entrained. For most types of exposed concrete a slight reduction in strength is far less significant than the improved resistance to frost action. The reduction in strength will rarely exceed 15 percent in the case of compressive strength and 10 percent in the case of flexural strength.

In some installations of precast concrete units such as cribbing and curbing, there is considerable exposure to freezing and thawing action. The use of adequately prepared and controlled air-entrained concrete is the best way to improve resistance to freezing and thawing.

(6) Air-Detraining Admixtures. There have been cases where aggregates have released gas into, or caused excessive air entrainment, in plastic concrete which made it necessary to use an admixture able to dissipate the excess air or other gas (MacNaughton and Herbich, 1954). Also, it is sometimes desirable to remove part of the entrained air from a concrete mixture. Compounds such as tributyl phosphate, diburyl phthalate, water-insoluble alcohols, and water-insoluble esters of carbonic and boric acids, as well as silicones, have been proposed for this purpose; however, tributyl phosphate is the most widely used material.

(7) Admixture to Reduce Alkali Aggregate Expansion. Test data indicate that small additions of certain chemical substances may be effective in decreasing expansion resulting from alkali-aggregate reaction (McCoy and Caldwell, 1951). Outstanding reductions in expansion of labora-

tory mortar specimens have been reported for additions of 1 percent by weight of the cement of lithium salts and for additions of about 2 to 7 percent of certain barium salts. Moderately reduced expansions were also obtained with certain protein air-entraining admixtures and with some water-reducing, set-retarding admixtures. It was found that some of these substances were more effective in reducing expansion than others. The results reported are limited and further work is needed. There is some evidence that expansions due to alkali-aggregate reaction are slightly lowered by air entrainment and the use of low alkali cement.

(8) Expansion Admixtures. Admixtures, which during the hydration period of concrete or grout expand themselves or react with other constituents of the grout to cause expansion, are used to minimize the effects of dry shrinkage. They are used in both restrained and unrestrained placement. The most common admixtures for this purpose is finely divided iron and chemicals to promote oxidation of the iron. This use is generally limited to relatively small projects. Expansive cements are most often used on large projects.

(9) Shrinkage Preventing Admixtures. Three different shrinkage-compensating cements are described in ASTM Standard C845 and are designated as Type K, Type S, and Type M. The expansion of each of these cements when mixed with sufficient water is due principally to the formation of ettringite. Most shrinkage-compensating cements consist of constituents of conventional portland cement with added sources of aluminate and calcium sulfate. The three types of expansive cements differ from each other in the form of the aluminate compounds from which the expansive ettringite is developed. The principal constituents of these cements are:

(a) Type K Portland cement, calcium sulfate, and Portland-like cement containing anhydrous tetracalcium trialuminate sulfate;

(b) Type M Portland cement, calcium sulfate, and calciumaluminate cement; and

(c) Type S Portland cement high in tricalcium aluminate and calcium sulfate.

An important requiremert is the selection of material proportions so that the Ca, S_3, and especially the Al_2O_3 become available for ettringite formation during the appropriate period after the mix water is added. Determination of these proportions should be based on test results in accordance with ASTM Standard C806.

(10) Bond Improvement Admixtures. Bonding admixtures are water emulsions of several organic materials that are mixed with Portland cement or mortar grout for application to an old concrete surface just prior to placing topping or patching mortar or concrete, or are mixed with the topping or patching material. Common bonding admixtures are made from polymers that include polyvinyl chloride, polyvinyl acetate, acrylics, and butadiene-styrene copolymer. Bonding agents usually cause entrainment of air and a sticky consistency in grout mixtures.

(11) Penetration and Plasticity Admixtures. Admixtures which improve the ability of freshly mixed concrete and grout to penetrate into voids and cracks also increase the plasticity of the mix. The degree of

plasticity of fresh concrete, the amount of surface area of the solids per unit of water volume, will determine the bleeding characteristics and workability of concrete and grout. A low ratio of surface area of solids to volume of water results in a thin and watery paste; consequently, the aggregate particles are only slightly separated and the mixture lacks plasticity and tends to segregate. The ratio of surface area of solids to volume of water may be increased by increasing the amount of cement or by adding a suitable mineral admixture to the mix. Admixtures that are relatively chemically inert, such as ground quartz or limestone, cemetitious materials such as natural cements, hydraulic limes or slag cements, and pozzolans are commonly used.

(12) Impermeability Admixtures. Concrete and grout are not impermeable to the penetration of water; however, the terms "waterproofing" or "damp proofing" have come to mean a reduction of rate of penetration of water into dry concrete and grout. Admixtures comprised of fatty acids, usually calcium or ammonium stearate or oleate, which also cause air entrainment during mixing. Also used are mineral oils, asphalt emulsions, and certain cut-back asphalts.

(13) Corrosion Inhibiting Admixtures. In the manufacture of certain concrete products containing steel, it might be desirable to accelerate the rate of strength development by use of both a chemical accelerator and heat. The latter is usually in the form of steam at atmospheric pressure. When calcium chloride is used as the accelerator in this type of curing, laboratory studies have found the rate of corrosion of the steel to be accelerated. However, Arber and Vivian (1961) found that certain compounds containing an oxidizable ion such as stannous chloride, ferrous chloride, and sodium thiosulfate, act as accelerators as does calcium chloride, but also appear to cause less corrosion than the latter. Stannous chloride appeared to be the best of the products tried and 2 percent of the salt by weight of cement was more effective than 1 percent, and as effective as greater amounts, both from the standpoint of acceleration and resistance to corrosion. For effective use, the salt must be added to the concrete in the stannous form and a dense concrete must be used.

(14) Color Admixtures. Pigments are often added to produce color in the finished concrete. The requirements of suitable coloring admixtures include:

(a) color fastness when exposed to sunlight;

(b) chemical stability in the presence of alkalinity produced in the set cement;

(c) no adverse effect on setting time or strength development of the concrete; and

(d) stability of color in autoclaved concrete products during exposures to the conditions in the autoclave.

Pigments frequently used to color concrete are:

(a) Grays to black--black iron oxide, mineral black, carbon black,

(b) Blue--ultramarine blue, Phthalocyanine blue,

(c) Red--red iron oxide,

(d) Brown--brown iron oxide, raw and burnt amber,

(e) Cream or buff--yellow iron oxide,

(f) Green--chromium oxide, phthelocyanine green, and

(g) White--titanium dioxide,

5. Preparation of Concrete Mixes.

There are standard methods for selecting proportions for concrete made with aggregates of normal density and of workability suitable for usual cast-in-place construction. The methods provide a first approximation of proportions and are intended to be checked by trial batches in the laboratory or field and adjusted, as necessary, to produce the desired characteristics of the concrete.

a. Selection of Mix Proportions. The procedure for selection of mix proportions given in this section is applicable to normal weight concrete. Estimating the required batch weights for the concrete involves a sequence of logical, straightforward steps which, in effect, fit the characteristics of the available materials into a mixture suitable for the work. Regardless of whether the concrete characteristics are prescribed by the specifications or are left to the individual selecting the proportions, estimation of a total batch weight per cubic unit of concrete can best be accomplished by referring to the table used in (7) below.

(1) Choice of Slump. If slump is not specified, a value appropriate for the work can be selected from Table 10. The slump ranges shown apply when vibration is used to consolidate the concrete. Mixes of the stiffest consistency that can be placed efficiently should be used.

Table 10. Recommended slumps for various types of construction.

Types of construction	Slump (mm)	
	Maximum[1]	Minimum
Reinforced foundation walls and footings	76	25
Plain footings, caissons, and substructure walls	76	25
Beams and reinforced walls	102	25
Building columns	102	25
Pavements and slabs	76	25
Mass concrete	51	25

[1]May be increased 25 mm for methods of consolidation other than vibration.

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MOFFATT AND NICHOL INC LONG BEACH CA FEB 83 CERC-SR-10
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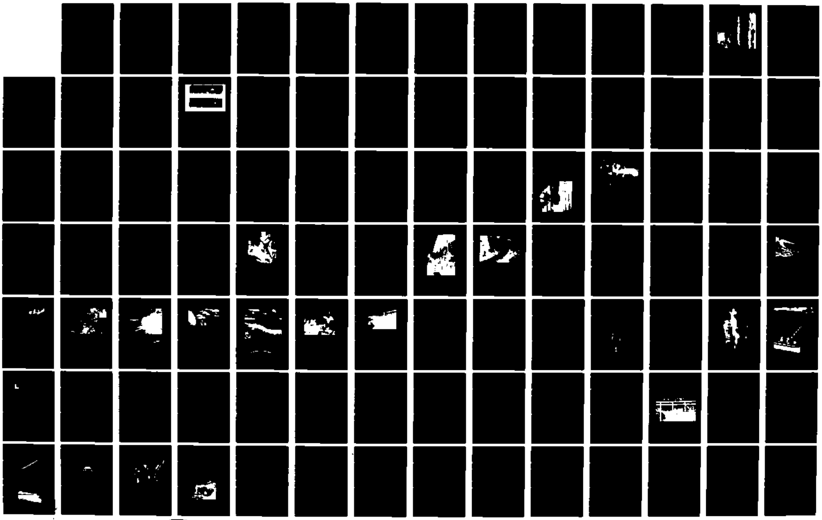


(2) Choice of Maximum Size of Aggregate. Large maximum sizes of well-graded aggregates have less voids than smaller sizes. Hence, concretes with the larger sized aggregates require less mortar per unit volume of concrete. Generally, the maximum size of aggregate should be the largest that is economically available and consistent with dimensions of the structure. In no event should the maximum size exceed one-fifth of the narrowest dimension between sides of forms, one-third the depth of slabs, nor three-fourths of the minimum clear spacing between individual reinforcing bars, bundles of bars, or pretensioning strands.

(3) Estimation of Mixing Water and Air Content. The quantity of water per unit volume of concrete required to produce a given slump depends on the maximum size, particle shape, and grading of the aggregates, and on the amount of entrained air. It is not greatly affected by the quantity of cement. Table 11 provides estimates of required mixing water for concretes made with various maximum sizes of aggregate, with and without air entrainment. Depending on aggregate texture and shape, mixing water requirements may be somewhat above or below the tabulated values, but they are sufficiently accurate for the first estimate. Such differences in water demand are not necessarily reflected in strength.

Table 11 indicates the approximate amount of entrapped air to be expected in nonair-entrained concrete in the right side of the table and shows the recommended average air content for air-entrained concrete in the left side of the table. The use of normal amounts of air entrainment in concrete with a specified strength near or about 34 megapascals (5 000 pounds per square inch) may not be possible due to the fact that each added percent of air lowers the maximum strength obtainable with a given combination of materials (Tuthill, 1960).

When trial batches are used to establish strength relationships or verify strength-producing capability of a mixture, the least favorable combination of mixing water and air content should be used. This is, the air content should be the maximum permitted or likely to occur, and the concrete should be gaged to the highest permissible slump. This will avoid developing an overoptimistic estimate of strength on the assumption that average rather than extreme conditions will prevail in the field.

(4) Selection of Water-Cement Ratio. The required water-cement ratio is determined not only by strength requirements but also by factors such as durability and finishing properties. The average strength selected must, of course, exceed the specified strength by a sufficient margin to keep the number of low tests within specified limits (Table 12). For severe conditions of exposure, the water-cement ratio should be kept low even though strength requirements may be met with a higher value. Table 13 gives limiting values.

(5) Calculation of Cement Content. The amount of cement per unit volume of concrete is fixed by the determinations made above. The required cement is equal to the estimated mixing water content divided by the water-cement ratio. If, however, the specification includes a separate minimum limit on cement in addition to requirements for strength and durability, the mixture must be based on whichever criterion leads to the larger amount of cement. The use of pozzolanic or chemical admixtures will affect properties of both the fresh and hardened concrete.

Table 11. Approximate mixing water requirements for different slumps and maximum sizes of aggregates[1] (Portland Cement Association, 1979).

Maximum size of aggregate (in)	Air-entrained concrete				Nonair-entrained concrete			
	Recommended average total air content, (pct)[2]	Slump (in)			Approximate amount of entrapped air, per cent	Slump (in)		
		1 to 2	3 to 4	5 to 6		1 to 2	3 to 4	5 to 6
		Water, (lb/yd^3 of concrete)[3]				Water, (lb/yd^3 of concrete)[3]		
3/8	7.5	310	340	360	3.0	350	385	410
1/2	7.5	300	325	340	2.5	335	365	385
3/4	6.0	275	300	315	2.0	310	340	360
1	6.0	260	285	300	1.5	300	325	340
1 1/2	5.0	240	265	285	1.0	275	300	315
2	5.0	225	250	265	0.5	260	285	300
3	4.0	210	235	-	0.3	240	265	-
6	3.0	185	200	-	0.2	210	235	-

[1]Adapted from Recommended Practice for Selecting Proportions for Concrete (ACI 613-54).
[2]Plus or minus 1 percent.
[3]These quantities of mixing water are for use in computing cement factors for trial batches. They are maximum for reasonably well-shaped angular coarse aggregates graded within limits of accepted specifications.

Table 12. Relationships between water-cement ratio and compressive strength of concrete.[1]

Compressive strength at 28 days, psi[2]	Water-cement ratio, by weight	
	Nonair-entrained concrete	Air-entrained concrete
6 000	0.41	--
5 000	0.48	0.40
4 000	0.57	0.48
3 000	0.68	0.59
2 000	0.82	0.74

[1]American Concrete Institute (ACI), 1979.

[2]Values are estimated average strengths for concrete containing not more than the percentage of air shown in Table 11. For a constant water-cement ratio, the strength of concrete is reduced as the air content is increased. Strength is in accordance with Section 9(b) of ASTM Standard C31.

Table 13. Maximum permissible water-cement ratios for air-entrained concrete in severe exposures.[1]

Type of structure	Exposure	
	Continuously or frequently wet and exposed to freezing and thawing	Exposed to seawater or sulfates[2]
Thin sections (railings, curbs, sills, ledges, ornamental work) and sections with less than 1 inch cover over steel	0.45	0.40
All other structures	0.50	0.45

[1]ACI, 1979.

[2]If sulfate-resisting cement (type II or type V of ASTM Standard C150) is used, permissible water-cement ratio may be increased by 0.05.

(6) Estimation of Coarse Aggregate Content. Varying the volume of coarse aggregate used per unit volume of concrete changes the workability of the mix. Given coarse and fine aggregates of available maximum size and gradation, respectively, the correct volume of coarse aggregate per unit volume of concrete must be chosen to produce satisfactorily workable concrete. The fine aggregate is characterized by its fineness modulus, a measure of the part of the coarse and medium sand, described in ASTM Standard C125. The fineness modulus increases with coarseness and is usually restricted to values between 2.3 and 3.1. The weight and volume characteristics of coarse aggregate are determined by tests on dry aggregate placed in thin layers and compacted by rodding.

The volume of coarse aggregate, in cubic feet, on a dry-rodded basis, for a cubic yard of concrete is equal to the value from Table 14 multiplied by 27. This volume is converted to dry weight of coarse aggregate required in a cubic yard of concrete by multiplying it by the dry-rodded weight per cubic foot of the coarse aggregate.

(7) Estimation of Fine Aggregate Content. At the completion of (6), all ingredients of the concrete have been estimated except the fine aggregate. Its quantity is determined by difference. Either of two procedures may be employed--i.e., the weight method or the absolute volume method.

If the weight of the concrete per unit volume is assumed or can be estimated from experience, the required weight of fine aggregate is simply the difference between the weight of fresh concrete and the total weight of the other ingredients. Often the unit weight of concrete is known with reasonable accuracy from previous experience with the materials. In the absence of such information, Table 15 can be used to make a first estimate. Even if the estimate of concrete weight per cubic yard is rough, mixture proportions will be sufficiently accurate to permit easy adjustment on the basis of trial batches.

(8) Adjustments For Aggregate Moisture. The aggregate quantities actually to be weighed out for the concrete must allow for moisture in the aggregates. Generally, the aggregates will be moist and their dry weights should be increased by the percentage of water they contain, both absorbed and surface. The mixing water added to the batch must be reduced by an amount equal to the free moisture contributed by the aggregate, i.e., total moisture minus absorption.

(9) Trial Batch Adjustments. The calculated mixture proportions should be checked by means of trial batches prepared and tested in accordance with ASTM Standard C192, "Making and Curing Concrete Compression and Flexure Test Specimens in the Laboratory," or full-sized field batches. Only sufficient water should be used to produce the required slump regardless of the amount assumed in selecting the trial proportions. The concrete should be checked for unit weight and yield (ASTM Standard C138) and for air content (ASTM Standard C138, C173, or C231). It should also be carefully observed for proper workability, freedom from segregation, and finishing properties. Appropriate adjustments should be made in the proportions for subsequent batches.

Table 14. Volume of dry-rodded coarse aggregate[1] per unit of volume of concrete.[2]

Maximum size of aggregate (in)	Fineness modulus of sand			
	2.40	2.60	2.80	3.00
3/8	0.50	0.48	0.46	0.44
1/2	0.59	0.57	0.55	0.53
3/4	0.66	0.64	0.62	0.60
1	0.71	0.69	0.67	0.65
1 1/2	0.75	0.73	0.71	0.69
2	0.78	0.76	0.74	0.72
3	0.82	0.80	0.78	0.76
6	0.87	0.85	0.83	0.81

[1]As described in ASTM Standard C29.

[2]ACI, 1979.

Table 15. First estimate of weight of fresh concrete.[1]

Maximum size of aggregate (in)	Weight (lb/yd^3)[2]	
	Nonair-entrained concrete	Air-entrained concrete
3/8	3 840	3 690
1/2	3 890	3 760
3/4	3 960	3 840
1	4 010	3 900
1 1/2	4 070	3 960
2	4 120	4 000
3	4 160	4 040
6	4 230	4 120

[1]ACI, 1979.

[2]Values calculated for concrete of medium richness (550 lb of cement per y^3) and medium slump with aggregate specific gravity of 2.7. Water requirements based on values for 76- to 102-mm (3 to 4 inches) slump in Tables 10 and 11.

b. Curing. Curing is essential in the production of quality concrete. The potential strength and durability of concrete will be fully developed only

if it is properly cured for an adequate period of time before being placed in service. Proper curing prevents loss of moisture for the time necessary to obtain necessary hydration of the cement. Excess mixing water is allowed to escape; however, the appearance of plastic shrinkage cracks in the surface of the concrete about the time the concrete is ready for finishing indicates that the paste is losing water too rapidly.

Concrete should be cured by keeping the concrete damp for not less than 7 days if made of normal Portland cement, and for not less than 3 days if made of high (early) strength cement. For each decrease of 2.7° below 21° Celsius (5° below 70° Farenheit), in the average curing temperature, the curing period shall be increased by 4 days for units made of normal Portland cement and by 2 days for units made of high (early) strength cement or until the concrete has attained its designed strength. Where units are cured by high-pressure steam, steam vapor, or other approved processes used to accelerate the hardening of the cement, the curing time may be reduced provided the compressive strength of the concrete is equal to that obtained by damp curing, equal to the 28-day strength. Concrete units shall not be moved from the casting bed until the curing period is complete.

(1) Methods of Curing. There are two general methods of retaining the required water for hydration furnished by the mixing water in concrete.

(a) Moist Environment. A moist environment can be maintained through water ponding, water sprays, steam, or saturated cover materials such as burlap or cotton mats, carpets (some carpets may contain certain dyes which inhibit the settling of concrete), earth, sand, sawdust or straw, all of which must be maintained continuously wet.

(b) Sealing Materials. Curing can also be accomplished by preventing the loss of mixing water by means of sealing materials or curing compounds. Sealing is accomplished by the use of impervious sheets of paper or plastics, or by the application of an impervious membrane-forming curing compound applied to the freshly placed concrete. Compounds consisting essentially of waxes, resins, chlorinated rubber, and solvents of high volatility at atmospheric temperatures are used extensively for curing concrete. The formulations must be such as to provide a moisture seal shortly after being applied and must not be injurious to Portland cement. Compounds should comply with the requirements of ASTM Standard C309.

Before applying curing compound, tops of joints that are to receive sealant shall be tightly closed with temporary material to prevent entry of the compound and to prevent moisture loss during the curing period. The compound shall be applied on damp surfaces as soon as the moisture film has disappeared. The curing compound shall be applied by power spraying equipment using a spray nozzle equipped with a wind guard. The compound shall be applied in a two-coat continuous operation at a coverage of not more than 10 square meters per liter (400 square feet per gallon) for each coat. When applied by hand sprayers, the second coat shall be in a direction approximately at right angles to the direction of the first coat. The compound shall form a uniform, continuous, adherent film that shall not check, crack, or peel, and shall be free from pinholes or other imperfections. Surfaces subjected to rainfall within 3 hours after compound has

been applied, or surfaces damaged by subsequent construction operations within the curing period shall be immediately resprayed at the rate specified above. Membrane curing compound shall not be used on surfaces that are to receive any subsequent treatment that depends on adhesion or bonding to the concrete. Membrane curing compound shall not be used on surfaces that are maintained at curing temperatures with free steam. Where membrane-forming curing compounds are permitted, permanently exposed surfaces shall be cured by use of a nonpigmented membrane-forming curing compound containing a fugitive dye. Where nonpigmented-type curing compounds are used, the concrete surface shall be shaded from the direct rays of the sun for the curing period. Surfaces coated with curing compound shall be kept free of foot and vehicular traffic, and from other sources of abrasion and contamination during the curing period.

(2) Special Conditions. There are some conditions of curing concrete for coastal structures that frequently occur and require special consideration.

(a) Hot Weather Concreting. High temperatures impact on concrete by more rapid hydration of cement, greater mixing water demand, increased evaporation of mixing water, reduced strength, and a tendency to crack either before or after hardening. Special precautions are necessary such as cooling the aggregate, adding ice to the concrete mix, and covering the curing concrete to keep it moist. Certain water-reducing retarders may counteract the accelerating hardening of concrete at high temperatures and reduce the need for additional mixing water. Curing concrete above 32.2^{o} Celsius (90^{o} Farenheit) is undesireable.

(b) Cold Weather Concreting. Fresh concrete should be maintained at a minimum temperature of 10^{o} Celsius (50^{o} Farenheit) until initial strength is attained. This requirement may require heating the aggregate and mixing water, not adding admixtures until the mixing water temperature is 32.2^{o} Celsius or below, and protecting the concrete surface from freezing temperatures until safe strength has developed in the concrete. Most of the heat of hydration is developed in the first 3 days of hardening; however, it may be necessary to provide housing or additional heat to ensure adequate temperature and moisture for curing to obtain the strength and durability intended of the concrete.

(c) Underwater Concrete Curing. No special precautions are usually feasible for curing concrete placed under water except for temperature control. Concrete will cure best in a temperature range of 10^{o} to 24^{o} Celsius. Higher temperatures will accelerate curing while lower temperatures will delay curing.

(3) Preferred Curing Method. Where physical conditions permit and to obtain a high durable concrete the following curing methods in order of performances are: (1) continuously drenched with water; (2) burlap, blankets or carpets continuously wet; (3) membrane-forming curing compounds; (4) sand or straw randomly dampened; and (5) air cured.

6. Techniques to Enhance Durability.

a. General. The designer and constructor-manufacturer share the responsibility to build concrete structures that remain essentially in their

original state despite attack of the environment. The ability of the structure to withstand environmental attack is called durability.

Concrete is an extremely durable material and ranks high among all known structural materials for its resistance to the attack of natural environments. Freeze-thaw and saltwater immersion tests have demonstrated the inherent resistance of concrete. It is generally accepted that properly designed prestressed concrete piles are among the most durable piling for marine structures, even in a tropical salt-spray environment.

Maintenance of durability is achieved only by proper design and construction. The consequences of disintegration and corrosion are potentially catastrophic. Corrosion and disintegration are not random or spot occurrences. Rather, when disintegration and disruption do take place, it is usually due to some fundamental error or neglect; the damage often extends to the entire structure. Thus, except for some localized spot of impact or accident, if disintegration is found, a thorough investigation should be made of the entire structure.

b. Impacts on Durability.

(1) Disruption. Durability is affected by disruption of concrete structure, environmental attacks, and use of aggregates. Disruption may take several forms:

(a) Disintegration of the concrete;

(b) chemical replacement in the concrete with a consequent loss of strength;

(c) corrosion of reinforcing bars and ties or prestressing tendons, causing loss of strength, fracture, or lower resistance to fatigue;

(d) corrosion of the inserts, embedded fittings, and connections; and

(e) corrosion of anchorages.

In combination these forms may interact to intensify disruption. For example, corrosion of reinforcing bars produces products that swell and cause disintegration of the concrete cover.

(2) Environmental Attacks. Exposure to environmental elements may result in attacks that could severely impair the serviceability of a concrete structure if it were not made sufficiently durable. Among the more common environmental attacks are the following:

(a) Those causing or accelerating disintegration of or change in the concrete:

(1) Reactive aggregates;

(2) unsound aggregates;

(3) cement containing high percentage of alkalis or high C_3A;

(4) freeze-thaw cycles;

(5) CO_2 in air or surrounding water;

(6) erosion and abrasion from cavitation, ice, surf, moving sand; and

(7) acids, sulphates, nitrates, or organic substances in mixing water or in surrounding water, as at discharge from chemical plants or in sewage structures.

(b) Those causing or accelerating corrosion of steel:

(1) Salt or alkalis on aggregates;

(2) chlorides in admixtures or water used for mixing and curing;

(3) chlorides in water surrounding concrete (salt-water), salt spray, salt fog;

(4) oxygen;

(5) sulphides combined with moisture on stressed tendons before encasement or protection;

(6) stray electric currents;

(7) alkalis in surrounding soils;

(8) high temperature;

(9) embedded metals other than steel, particularly copper and aluminum;

(10) inadequate thickness of concrete cover, or permeability of cover;

(11) cracks;

(12) cement chemistry (e.g., too low C_3A); and

(13) deicing salts, acids, or other aggressive chemicals.

c. Enhancement Techniques. Fortunately, the steps to be adopted to overcome these many forms of attack are complementary to each other. Most have been adopted as standard good practice.

(1) Aggregates. Although aggregate is commonly considered to be an inert filler in concrete, this is not always the case. Certain aggregates can react with Portland cement, causing expansion and deterioration.

Fortunately, care in the selection of aggregate sources, and use of low alkali cement and pozzolans, where appropriate, will minimize this problem significantly.

All aggregates should be sound, non-reactive and abrasion resistant, and free from salt or alkalis. Particular care should be taken when working with aggregates from new sources, especially those with siliceous rocks and in desert areas. Sands from deposits several miles from the shores of the Persian Gulf are heavily contaminated with salt from salt fog; their use, unwashed, has led to serious corrosion in mild steel reinforcing.

Aggregates should meet the requirements of ASTM Standard C33 and, in addition, should be judged for their durability by an engineer, based on prior experience with the particular aggregates involved and tests. Tests are especially necessary when working with new aggregates. These tests, listed in ASTM C33, include tests for soundness (sodium-sulfate soundness test), alkali-aggregate reactivity, cement-aggregate reactivity, and freeze-thaw durability. Washing aggregates with freshwater will remove salt and dust from sand and aggregates.

(2) Reinforcing Steel Protection. The spalling of concrete in bridge decks and marine structures, such as reinforced wharf decks, piles, groins, and concrete anchors, has been a serious problem for many years. The principal cause is corrosion of the reinforcing steel, which is largely due to the use of deicing salts, exposure to seawater, or inadequately embedded reinforcing steel (Fig. 16). The corrosion products produce an expansive force which causes the concrete to spall out about the steel. A minimum cover over the steel of 76 millimeters (3 inches) and use of a low-permeability, air-entrained concrete will ensure good durability in the great majority of cases, but more positive protection is needed for very severe exposures.

(a) Sufficient Cover. The concrete cover protects the steel by creating a passive condition of high pH at the surface of the steel. Too thin a cover allows carbonation, usually around the surface of the coarse aggregate particles. Carbonation lowers the pH. Oxygen is necessary to the corrosion mechanism; a thicker cover minimizes the movement of oxygen to the steel surface. In seawater, chloride ion movement is also inhibited by thicker covers. The cover should properly be related to the density and cement content. The exact relationships have not been thoroughly established, so arbitrary values are usually used as guides or standards. Thicker covers make it possible to achieve better compaction, fewer voids, and less permeability.

(b) Reinforcing Steel Coating. Concrete may not provide permanent protection of reinforcing bars under many conditions. Cracks in the concrete surface contribute to corrosion in providing access to moisture, air and contaminants. Hydrated Portland cement is subject to chemical reaction with carbon dioxide of the atmosphere. Carbonation reduces the alkalinity of concrete thus reducing its effectiveness as a protecting medium. Concretes will also deteriorate from other causes such as freeze-thaw cycles, sulfate attack, reactive aggregates, or other causes; it will crack or weaken and thus become less able to protect embedded reinforcing.

Figure 16. Exposed steel reinforcement due to spalling of concrete cover.

Corrosion of steel reinforcing can also result from stray electrical current or corrosion cells that develop on the embedded steel. Electrical potential differences can occur in various spots in concrete containing metals because of differences in moisture content, oxygen concentration, electrolyte concentration, and by contact of dissimilar metals. A corrosion cell results when regions of different electrical potential are interconnected by a conductive pathway. Loss of metal then occurs at the region of more positive potential (anode).

One recently developed method of preventing reinforcing steel deterioration is to coat the bars with an epoxy material. The epoxy is applied in

a mill or coating facility usually by a fusion-banding process as a result of an irreversible heat--catalyzed chemical reaction. The careful application of a fusion-bonded or electrostatically applied epoxy coating has produced virtually pinhole-free coating protection of the steel bars from the moisture, chlorides and other contaminates that may be in or enter the concrete.

Fusion-bonded epoxy coatings have had a short but successful history of protecting reinforcing steel against corrosion in a highly alkaline and chloride contaminated environment. The fusion-bonding epoxy coating if formed by combining an epoxy resin with appropriate curing agent, pigments, catalysts, flow control agents, etc. to achieve the desired application and performance characteristics.

Fusion bonded means that the coating achieves adhesion as a result of a heat-catalyzed chemical reaction. When a fusion-bonded coating is exposed to heat, a chemical reaction occurs; and sufficient heat must be supplied for a given amount of time to allow that chemical reaction to reach completion. The reaction is irreversible. Unlike thermoplastic coatings, if heated after the coating is cured, it will not soften. The material is applied to rebars at a mill away from the job site and is therefore not weather dependent as is coated under controlled conditions.

The coating system is composed of four parts: surface preparation, material selection, application, and cure. Surface preparation requires sandblasting to white metal since the surface must be completely clean and possess an anchor pattern. It is desirable that both physical and chemical adhesion be obtained. Materials selection can be made from those commercially available that are selected in accordance with ASTM Standard D3415. Application is accomplished by heating the rebar with a noncontaminating heat source to approximately 232° Celsius (450° Farenheit) but as recommended by the manufacturer. The resin application should be by electrostatic deposition to obtain an even coating of 0.13 to 0.26 millimeter (5 to 10 mils) thick. Heat is continued until the gel time has been satisfied. The bars are then cooled, followed by an electrical holiday inspection. Following this type of coating application rebars can be transported to job site and bent to necessary configurations with reasonable ease.

(c) Prevention of Cracks. Cracks allow carbonation penetration and are also a route for oxygen to the surface of the steel. Cracks may further play a part in electrolytic cell formation in the concrete.

(d) Elimination of Voids at Steel Surface. Studies, indicate that steel corrosion is associated with a void at the steel surface. This can be diminished by mix design and thorough consolidation. In posttensioning, grouting procedures should be adopted which will prevent or minimize these voids.

(e) Proper Grouting of Ducts in Posttensioned Concrete. Proper grouting is essential for corrosion protection and prevention of bursting during freezing.

(3) Abrasion Resistance. The abrasion resistance of concrete is defined as the "ability of a surface to resist being worn away by rubbing and friction." Research to develop meaningful laboratory tests on concrete

abrasion has been underway for more than a century. The problem is complicated because there are several different types of abrasion, and no single test method has been found which is adequate for all conditions. Abrasion can be classified into four types:

(a) Wear on concrete floors due to foot traffic and light trucking, skidding, scraping, or sliding of objects on the surface (attrition);

(b) wear on concrete road surfaces due to heavy trucks and automobiles with studded tires or chains (attrition, scraping, and percussion);

(c) erosion in hydraulic structures such as dams, spillways, tunnels, bridge abutments, concrete breakwaters, and piling due to the action of abrasive materials carried by flowing water (attrition and scraping); and

(d) wear on concrete dams, spillways, tunnels, and other water-carrying systems where high velocities and negative pressures are present (generally known as cavitation erosion, which is mainly the result of design and is not covered in this guide).

To properly evaluate abrasion resistance, the type of concrete being tested must be considered. If it is of the same mix throughout, the abrasion resistance can be expected to be a direct function of the concrete strength. If, however, metallic or other hardeners have been applied, the time required for the abrasion apparatus to penetrate the hard surface must be determined to properly evaluate the test results.

(a) Factors Affecting Abrasion Resistance of Concrete. The abrasion resistance of concrete is affected primarily by compressive strength, aggregate properties, finishing methods, use of toppings, and curing.

Tests and field experience have generally shown that compressive strength is the most important single factor controlling the abrasion resistance of concrete, with abrasion resistance increasing with increase in compressive strength. Compressive strength and abrasion resistance vary inversely with the ratio of voids (water plus air) to cement. For rich mixes, limiting the maximum size of the aggregate will improve compressive strengths and result in maximum abrasion resistance of concrete surfaces.

Proper finishing procedures and timing are essential if the quality of concrete near the surface of a slab is to be as good as that for the underlying section. Delaying the floating and troweling operations increases resistance to abrasion. Another highly important ingredient in wear-resistant, nondusting concrete surfaces is adequate curing (ACI 308-71). One study showed that a surface cured for 7 days is nearly twice as wear-resistant as one cured for only 3 days, and additional curing resulted in further improvement.

(b) Recommendations for Obtaining Abrasion-Resistant Concrete Surfaces. The following measures will result in abrasion-resistant concrete surfaces.

1 Compressive Strength and Aggregate Properties. For a required concrete strength level, the strength selected should be appropriate for both the service exposure and the life of the structure. In no case should the compressive strength be less than 28 ˋgapascals (4 000 pounds per square inch). Suitable strength levels may ᵇe attained by:

(a) A low water-cement ratio,

(b) proper grading of fine and coarse aggregate (meeting ASTM Standard C33), limiting the maximum size to nominal 25 millimeters (1 inch);

(c) lowest consistency practicable for proper placing and consolidation with maximum slump of 75 millimeters (3 inches), and 25 millimeters for toppings;

(d) minimum air content consistent with the exposure conditions. For indoor floors not subjected to freezing and thawing, air contents of 3 percent or less are preferable; in addition to a detrimental effect on strength, high air contents can cause blistering, particularly when using dry shakes; and

(e) when wear conditions are severe, a high strength (not less than 34 megapascals (5 000 pounds per square inch)) topping layer, called a two-course floor, limiting the maximum size of aggregate to 12 millimeter (1/2 inch) in the topping.

2 Proper Finishing Procedures. Delay floating and troweling until the concrete has lost its surface water sheen or all free water on the surface has disappeared or been carefully removed. The delay period is usually for 2 or more hours after placing the concrete (depending on temperatures, mix proportions, and air content). Follow the recommendations of ACI Standards 302-69 and 304-73 with respect to finishing unformed surfaces.

3 Vacuum Dewatering. Vacuum dewatering is a method of removing excess water from concrete immediately after placement. The process results in increased strength, hardness, and wear resistance of concrete surfaces; it is primarily applicable to slab.

4 Special Dry Shakes and Toppings. Where severe wear is anticipated, the use of special toppings or dry shakes (such as coats of cement and hard fine aggregate, or of cement and iron aggregate) should be considered and, if selected, the recommendations of ACI Committee 302 (1969), "Recommended Practice for Concrete Floor and Slab Construction," should be followed.

5 Proper Curing Procedures. Curing should start immediately after the concrete has been finished and be continued for at least 7 days with type I cement (5 days with type III). Curing with water by spray, damp burlap, or cotton mats is preferred, provided the concrete is kept continuously moist. Waterproof paper or plastic sheets are satisfactory, provided the concrete is first sprayed with water and then immediatley covered with the paper or plastic with the edges overlapped and sealed with

waterproof tape. Curing compounds meeting ASTM Standard C309 seal the moisture in the concrete and are economical and easy to apply; they may be used where other methods are impracticable. The curing compound should be covered with scuff-proof paper if a floor area must be used before curing is completed.

(4) Freezing and Thawing. Freezing and thawing damage is a serious problem in northern climates, however, the mechanisms involved are now fairly well understood. Exposing damp concrete to freezing and thawing cycles is a severe test of the material, and poor concrete will certainly fail. In pavements the damage is greatly accelerated by the use of deicing salts, often resulting in severe scaling at the surface. Fortunately, air-entrained concrete which is properly proportioned, manufactured, placed, finished, and cured will almost always resist cyclic freezing for many years. It should be recognized, however, that even good concrete may suffer damage from cyclic freezing in unusual conditions, particularly concrete which is kept in a state of nearly complete saturation. Also, in cases where the concrete is saturated on the back side and exposed to air on the front side, it may exhibit extremely variable behavior, ranging from complete freedom from damage to total failure.

There is general agreement that cement paste can be made completely immune to damage from freezing temperatures by means of entrained air, unless special exposure conditions result in filling of the air voids. However, air entrainment alone does not preclude the possibility of damage of concrete due to freezing. Freezing phenomena in aggregate particles must also be taken into consideration (see test samples in Fig. 17).

(a) Freezing in Aggregate Particles. Most rocks have pore sizes much larger than those in cement paste, and they expel water during freezing. The size of the coarse aggregate has been shown to be an important factor in its frost resistance. The critical size of rocks of good quality range upwards from perhaps a quarter of an inch. However, some aggregates (e.g., granite, basalt, diabase, quartzite, marble) have capacities for freezable water so low that they do not produce stress when freezing occurs, regardless of the particle size. The role of entrained air in alleviating the effect of freezing in rock particles is minimal.

(b) Overall Effects in Concrete. Without entrained air, the paste matrix surrounding the aggregate particles may fail when it becomes critically saturated and is frozen. However, if the matrix contains an appropriate distribution of entrained air voids characterized by a spacing factor less than about 200 micrometers (8 mils), freezing does not produce destructive stress. If absorptive aggregates (such as structural light-weight) are used and the concrete is in a continuously wet environment, the concrete will probably fail when the coarse aggregate becomes saturated. The pressure developed when the particles expel water during freezing ruptures the particles and the matrix. If the particle is near the concrete surface, a popout can result.

Whatever the absorption characteristics of a given aggregate, its rate of absorption in concrete is limited by the rate at which water can pass through its envelope of hardened cement paste. Because the coefficient of permeability of hardened cement paste is lower as its cement content

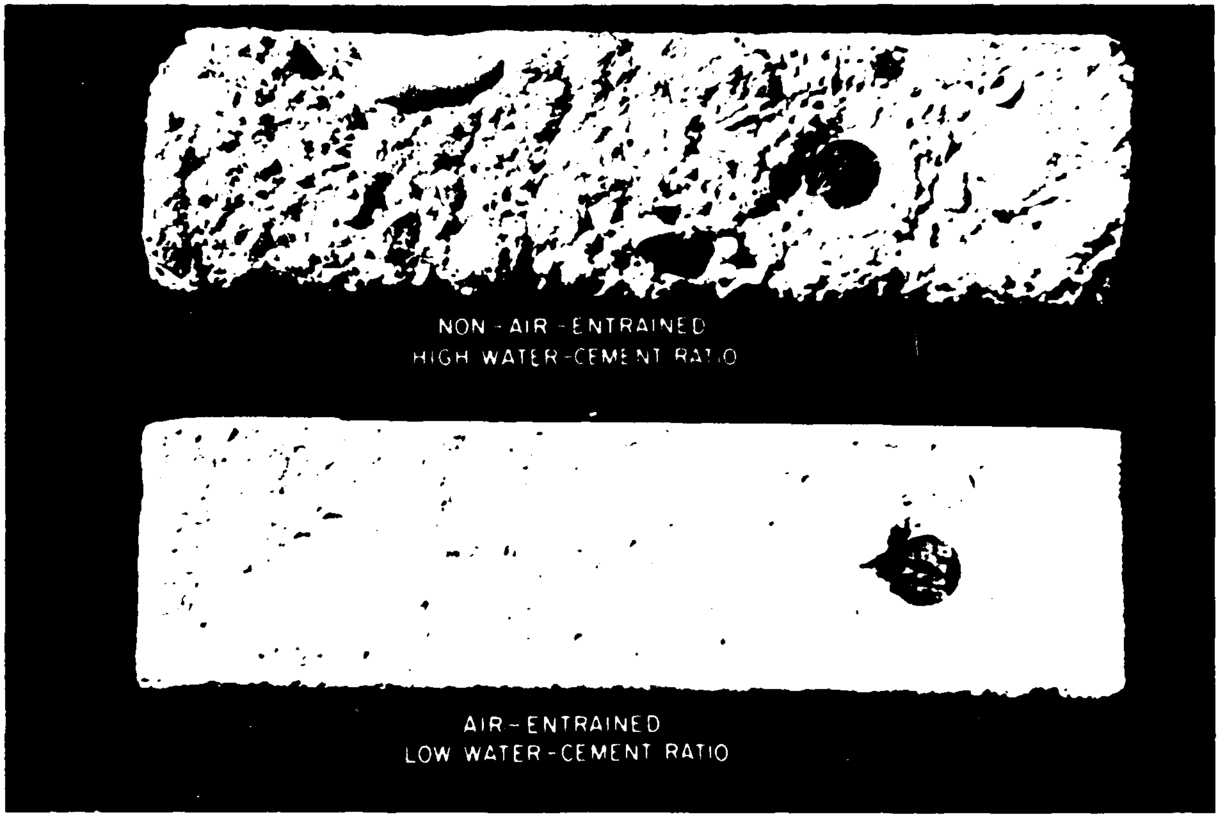


Figure 17. Test samples subjected to 150 cycles of freezing and thawing.

increases and the longer it has wet-cured, the rate of absorption of any kind of aggregate can be lowered by reducing the water-cement ratio of the paste and by requiring good curing.

(c) Recommendations for Durable Structures. Concrete which will be exposed to a combination of moisture and cyclic freezing requires the following:

(1) Design of the structure to minimize exposure to moisture;

(2) low water-cement ratio;

(3) air entrainment;

(4) suitable materials;

(5) adequate curing; and

(6) special attention to construction practices.

Requirements for the water-cement ratio and air entrainment are described in detail below.

(d) Water-Cement Ratio. Frost-resistant regular weight concrete should have a water-cement ratio not to exceed the values given in Table 13. Because the determination of the rate of absorption for lightweight aggregates is uncertain, it is impracticable to calculate the water-cement ratio of concretes containing such aggregates. For these concretes, a specified 28-day compressive strength of 27.6 megapascals (4 000 pounds per square inch) is recommended. For severe exposures, some have found it also desirable to specify a minimum cement content of 3.28 kilonewtons per cubic meter (564 pounds per cubic yard), and only that amount of water necessary to achieve the desired consistency.

(e) Entrained Air. Too little entrained air will not protect cement paste against cyclic freezing. Too much air will unduly penalize the strength. About 7 percent of air in the mortar for severe exposure, and about 5 percent for moderate exposure are reasonable. Frequent determinations of the air content of the concrete should be made. For regular weight concrete, the following test methods may be used: volumetric method (ASTM Standard C173), pressure method (ASTM Standard C231), or the unit weight test (ASTM Standard C138). An air meter may be used to provide an approximate indication of air content. For lightweight concrete, the volumetric method is recommended.

The air content and other characteristics of the air void system in hardened concrete may be determined microscopically (ASTM Standard C457). ASTM Standard C672 is often used to assess the resistance of concrete to deicer scaling.

d. Summary. Table 16 summarizes various techniques and practices that may be employed to obtain maximum durability.

7. Reinforcing-Prestressing Materials.

a. Steel Reinforcing. Steel reinforcing should conform to the following ASTM requirements:

(1) Bar reinforcement, ASTM Standard A615 Grade 40 or 60;

(2) cold drawn wire, ASTM Standard A82; and

(3) welded wire fabric, ASTM Standard A185, when zinc coated (galvanized), not less than 2.39 newtons per square meter (0.8 ounce per square foot) of Grade 5 "Prime Western" conforming to ASTM Standard B6.

b. Steel, Prestressed. High tensile steel is almost the universal material for producing prestress and supplying the tensile force in prestressed concrete. Such steel can take any of three forms: wires, strands, or bars. The most widely used at present are the strands, which are grouped, in parallel, into cables. Strands are fabricated in the factory by twisting wires together, thus decreasing the number of units to be handled in the tensioning operations. Steel bars of high strength have

Table 16. Techniques to obtain maximum durability.

Aggregates	Sound Non-reactive Abrasion-resistant
Cement	Low alkali content (less than 0.6 pct Na_2O + K_2O) Moderate C_3A (for marine environments) High cement factor
Water	Freshwater Free from chlorides and sulphates
Concrete mix	Low water-cement ratio Clean, small-size coarse aggregate Dense grading High-bond aggregate (where exposed to abrasion or cavitation) Limitation on chlorides from any source
Admixtures	Water-reducing Nonsegregating Air-entrainment (for freeze-thaw environments)
Forms	Smooth surfaced No reentrant angles, projections, etc. No sharp corners, edges
Placing	Thoroughly consolidated and compacted Minimum bleed holes
Cover	Adequate cover over mild steel Adequate cover over prestressing steel
Finish	Troweled
Construction joints	Well prepared Well bonded (by presoaking and grout or by epoxy)
Curing	Adequate water cure or steam cure Moisture available or sealed in during cooling period Drying after curing (for marine freeze-thaw environments) Water free from chlorides or sulfates
Mild steel reinforcement	Free from pitting Well-distributed bars Use of very large bars avoided
Embedded metals	Avoid galvanic action, especially Cu and Al Ducts to be thoroughly cleaned and flushed with freshwater or freshwater containing inhibitor
Prestressing steel	Free from pitting and extensive surface rust Clean and dry No salt Galvanized or plastic or epoxy-coated (for special cases only) Coating must not be abraded Kept free from corrosion by (a) VPI powder, (b) greases, (c) sealing, (d) limited time of exposure until finally grouted or protected High degree of prestress
Anchorages	"Flush-type," with the anchors themselves in pockets Epoxy concrete is best material
Grouting	Follow best grouting practice
Coatings	Bitumastic Epoxy Metallic sheeting (for special cases only, e.g., chemical) Wood lagging

also been developed and successfully applied to prestressed concrete, resulting in considerable economy at times.

The prestressing wires now in the market are mostly high tensile wires obtained by cold-drawing high tensile steel bars through a series of dies. The process of cold drawing tends to realine the crystals, and the strength of the wires is increased by each drawing so that, the smaller the diameter of the wires, the higher their ultimate unit strength. The ductility of wires, however, is somewhat decreased as a result of cold drawing. It must be recognized that the actual strength will vary with the composition and manufacture of the wire as well as with its diameter.

The "as-drawn" wire, although possessing a high ultimate strength, has a relatively low proportional limit, e.g., about 414 to 552 megapascals (60 000 to 80 000 pounds per square inch), above which the stress-strain curve flattens at an increasing rate. This is objectionable, since the deformation characteristics are relatively uncertain and the amount of elongation during prestress cannot be easily determined. Hence various methods commercially known as the "stress-relieving" process have been used to increase the proportional limit of the "as-drawn" wire. Two common stress-relieving methods are as follows.

(1) Time-Stress Treatment. This treatment consists of stretching the wire to a stress level higher than that to be used in the final application. This increases the proportional limit to about 60 or 70 percent of the ultimate strength while the ultimate strength itself remains about the same. After this process of stretching, the wire will still have slight creep at an eventual stress of 50 percent of the ultimate, but, when stressed up to 70 percent, the creep will not be much more than 5 percent.

(2) Time-Temperature Treatment. This consists of heating the wire to 399^{o} to 427^{o} Celsius (750^{o} to 800^{o} Farenheit) for a period of 30 to 40 seconds. The heating is accomplished by drawing the wire through a molten lead bath, or through a hot-air tunnel such as a ceramic tube with heat applied on the outside. This treatment will have an effect on the proportional limit and ultimate strength of the wire similar to that of the previous process. But this "time-temperature treated" wire has practically no creep when subjected to 50 percent of the ultimate strength. At 60 percent of the ultimate strength it shows slightly more creep than the "stretched" wire, and at 70 percent and above the creep becomes excessive.

It is usually left to the engineer to specify the physical properties and sometimes the chemical composition desired. The chemical composition of prestressing wire may vary with the manufacturer. Some manufacturers may use a certain amount of silicon in the steel, although this is not included in the following sample analysis:

Carbon	0.60 to 0.85 percent
Manganese	0.70 to 1.00 percent
Phosphorus	0.050 percent maximum
Sulfur	0.055 percent maximum

In the United States, there are two kinds of high tensile wire strands available--one for pretensioning and another for posttensioning. Pretensioning strands are made of seven or more small uncoated wires as drawn. The strands are then drawn through a lead bath for stress-relieving and also to improve their bond characteristics. For posttensioning and unbonded work, strands consisting of 7 to 61 galvanized wires are produced. These strands are machine fabricated and stress-relieved to increase their proportional limit and to minimize creep. When the strands are to be bonded to the concrete, the wires should preferably be ungalvanized.

High strength bars up to 1 034 megapascals (150 000 pounds per square inch) or more are made by cold-working special alloy steels. By alloying high carbon steel with proper agents such as silicon and manganese, high strength is obtained. Then the proportional limit is raised by cold working. The chemical contents of these bars again may differ. A sample composition of high strength steel bars is:

Carbon	0.6 percent
Silicon	2.0 to 2.5 percent
Manganese	0.7 to 1.0 percent
Phosphorus	0.2 percent
Sulfur	0.2 percent

To get a better bond between steel and concrete, various forms of surface indentation afford direct mechanical keys with the surrounding concrete. It is assumed that the corrugations now commercially used will not alter the stress-strain properties of the wires, although some question has been raised as to their fatigue strength in comparison with the straight ones. Some pretensioning factories pass their wires through a small machine, forming permanent waves which are believed to increase the bond resistance of the wire.

The ultimate strength of steel wires, strands, or bars varies with their manufacture, so that it is frequently necessary to obtain sample tests for each lot of products. However, the general range of values is listed in Table 17. While the ultimate strength of high strength steel can be easily determined by testing, its elastic or proportional limit, or its yield point, cannot be so simply ascertained. First, there is no yield point for high strength steel as there is for ordinary low carbon steel. Second, the gradual curving of the stress-strain curve makes it difficult to fix a point for the proportional limit. Consequently, different methods for defining the yield point of high tensile steel have been adopted.

Yield point and proportional limit must be obtained by testing the particular steel. But as a rough approximation Table 18 gives the usual values for high tensile steels expressed in terms of the respective ultimate strength. Approximate average values for the secant modulus at the proportional limit are shown in Table 19.

In order to avoid brittle failures in the prestressed concrete, a certain amount of ductility in the steel is desirable. This is measured by the amount of elongation in a certain gage length, generally a 254-millimeters (10-inch) gage in this country. The average ultimate elongation is about 5 percent for wires and 5 percent for bars. For evident reasons, it

Table 17. Strength of steel wires.

Wires	Ultimate Strength, (MPa)
Wires of varying diameters and make	1 379 - 2 275
Strands of 7 uncoated small wires	1 586 - 1 862
Strands of 19 or more galvanized wires	1 379 - 1 517
Strands of 19 or more uncoated wires	1 517 - 1 655
Bars	965 - 1 172

Table 18. Approximate yield point and proportional limit.

	Yield point at 0.2-pct set $(f'_s)^1$	Proportional limit $(f'_s)^1$
Wires as drawn	0.75	0.35
prestretched	0.85	0.55
time-temperature treated	0.87	0.70
galvanized	0.85	0.55
Strands, pretensioning as drawn	0.85	0.35
stress-relieved	0.90	0.75
Strands, posttensioning prestretched	0.85	0.55
Bars	0.90	0.60

[1]Ultimate strength

Table 19. Secant modulus at proportional limit.

	Secant modulus (MPa)
Wires	186 159 - 206 843
Strands for pretensioning and stress-relieved	186 159 - 199 948
Strands for posttensioning and prestretched	165 474 - 179 264
Bars	172 369 - 193 053

cannot be easily measured for strands; only the wires making up the strands are measured for ductility.

(3) Steel, Creep Characteristics. One of the important characteristics required of prestressing steel is minimum creep under maximum stress. Creep in steel is the loss of its stress when it is prestressed and maintained at a constant strain for a period of time. It can also be measured by the amount of lengthening when maintained under a constant

stress for a period of time. The two methods give about the same results when the creep is not excessive, but the constant strain method is more often employed as a basis for measurement, because of its similarity to the actual conditions in prestressed concrete. Creep varies with steel of different compositions and treatments; hence exact values can be determined only by test for each individual case if previous data are not available.

Approximate creep characteristics, however, are known for most of the prestressing steels now in the market. Speaking in general, the percentage of creep increases with increasing stress, and when a steel is under low stress, the creep is negligible. The following summarizes the creep characteristics of different steels. Compared to stress-relieved wires, the "as-drawn" wires have somewhat higher creep. Prestretched wires will have about 2 to 3 percent creep when subject to 0.50 f_s' (f_s' = ultimate strength) but when stressed to 0.70 f_s', the creep will still be no more than 5 percent. Time-temperature treated wires have practically no creep when subject to 0.50 f_s'. At 0.60 f_s', it has slightly more creep than "prestretched" wires, and at 0.70 to 0.80 f_s' the creep becomes excessive. Galvanized wires have about the same creep characteristics as the time-temperature treated wires, and should preferably not be subjected to any stress above 0.60 f_s' without carefully considering the effect of creep. For high tensile bars, some limited tests seemed to show that, for stress up to about 0.55 f_s', creep is not more than 5 percent.

While creep in steel is a function of time, there is evidence to show that under the ordinary working stress for high tensile steel, creep takes place mostly during the first few days. Under constant strain, creep ceases entirely after about 2 weeks. If the steel is stressed to a few percent above its initial prestress and overstress is maintained for a few minutes, the eventual creep can be greatly lessened; it practically stops in about 3 days.

In order to prevent corrosion in unbonded prestressed concrete, wires are sometimes galvanized. When galvanized, the tensile strength is slightly reduced, but its other characteristics are similar to those of the time-temperature treated wire. It has practically no creep when used within 55 percent of its ultimate strength, but its tendency to creep at stresses above 55 percent cannot be well controlled.

c. Embedded Hardware. Embedments are common to all concrete construction. The materials are usually steel and generally consist of fabricated structural steel materials such as plates, angles, bars and sleeves; reinforcing steel of varying grades and strengths; and prestressing tendons such as wires, strands, and bars. Occasionally, other materials such as stainless steel, copper pipe, bronze plates, and Teflon are employed. Structural connections usually require the greatest care during the construction process.

For all embedments, care must be taken to ensure no disintegration of the concrete. Metal hardware must be protected from corroding either by sufficient concrete cover, alloying, or coatings. Common forms of coating are galvanizing or use of epoxy. All metal embedments should be protected from chlorides or sulfides or possibly other negative ions occurring in a

humid atmosphere if such materials are subject to any stress in the concrete. Exposures in industrial atmosphere may lead to H_2S concentrations that can cause brittle fracture in the hardware. Metallizing hardware with high corrosion resistant material, by flame or arc application, is an optional method of protecting metal hardware. These failures are generally classified as one form of hydrogen embrittlement which occurs when molecular hydrogen ions are able to enter between the steel molecules. This condition may also develop when dissimilar metals such as aluminum or zinc are used in the vicinity of steel.

8. Joint Sealing

a. General. Nearly every concrete structure has joints (or cracks) that must be sealed to ensure its integrity and servicability. It is a common experience that satisfactory sealing is not always achieved. The sealant used or its poor installation usually receive the blame, whereas often there have been deficiencies in the location or the design of the joint that would have made it impossible for any sealant to have done a good job.

This section shows that, by combining the right sealant with the right joint design for a particular application and then carefully installing it, there is every prospect of successfully sealing the joint and keeping it sealed. This section is a guide to what can be done rather than a recommended practice because in most instances there is more than one choice available. Without specific knowledge of the structure, its design, service use, environment, and the amount to be spent, it is impossible to prescribe a "best joint design" or a "best sealant." The information contained in this guide is, however, based on current practices and experience judged sound by many agencies and organizations. It should therefore be useful in making an enlightened choice of a suitable joint sealing system and ensuring that it is then properly detailed, specified, installed, and maintained.

b. Rigid Joints and Joining Materials. Prefabricated concrete units require field joining to establish structural continuity of the structure. Grout material proportions, as in conventional concrete practice, are influenced by structural design requirements. Additionally, the grout must be so designed as to flow freely into the joint space or voids without appreciable segregation or water gain so that honeycombing is avoided and intimate bond between the concrete surfaces is assured. Slurries of Portland cement and water, with or without sand, have long been used in the construction industry as a grout for filling cracks, voids, and joints. Later development of epoxy formulations, uniquely suited for use as an adhesive with concrete, lead to their commonly accepted use as concrete grouting and joining material in concrete construction.

(1) Cement Sand Grouts. Commonly employed grout material proportions of cement to sand range from 1:1 to 1:2; although ratios as lean as 1:3 have been used. With a 1:3 proportion of cement to sand, the water to cement ratio, by weight, for grout containing sand of average gradation (fineness modulus of 2.75) may be approximately 1:0.9. With lower cement to sand ratios, the w/c would also be lower, which increases the strength

of the grout. Compressive strength and placeability may limit the amount of sand that can be used in a grout as it must be sufficiently fluid to penetrate and fill all of the voids and joint space, yet be of a consistency that the suspended sand and cement do not filter out. Pozzolan is used to improve fluid properties of the mix, and to reduce segregation of solid particles. Usually, the proportions of cement to pozzolan are 2:1, although ratios as low as 1:1 and up to 9:1 have been used. For structural grout, it is usually not desirable to exceed a cement to sand ratio of 1:2 by weight, because higher ratios produce lower strengths and excessive segregation of sand in the grout mixture. The ratio of water to cement plus pozzolan (w/c+p), by weight, should range from 1:0.45 to 0.50.

(2) Epoxy Grout. Epoxy compounds are generally formulated in two or more parts. Almost without exception, epoxy systems must be formulated to make them suitable for specific end uses. There are many reasons why epoxies make good adhesives: they may be in liquid form and contain no volatile solvent, they adhere to most materials used in construction, no by-products are generated during curing, curing shrinkage is low, long-term dimensional stability is good, and they have high tensile and compressive strengths. Appropriate formulations are resistant to the action of weathering, moisture, acids, alkalis and many other environmental factors.

Epoxy resins find wide application as grouting materials. The filling of cracks, either to seal them from the entrance of moisture or to restore the integrity of a structural member is one of the more frequent applications. Cracks or joints 6 millimeters (0.25 inch) or less are most effectively filled with a pourable epoxy compound, whereas an epoxy resin mortar should be used for wider openings. Surfaces upon which epoxy compounds are to be used must be given careful attention as the bonding capability of a properly selected epoxy compound is primarily dependant on surface preparation. All surfaces must be meticulously cleaned and dry and be at proper surface temperature at the time of epoxy application. If impracticable or impossible to obtain a dry surface, an epoxy system formulated to bond to damp surfaces must be used. For the best performance under each condition of use, the properties of the epoxy resin system should be tailored to meet the specific needs of each type of application. It is unlikely that a system containing only an epoxy resin and a pure hardening agent will find wide use. It is for this reason that epoxy resin systems sold commercially are generally the products of formulators who specialize in modifying the system with flexibilizers, extenders, diluents and fillers to meet specific end-use requirements and it is important to adhere to the formulator's recommendation for use.

In mixing epoxy components accuracy is required and although a tolerance of plus or minus 5 percent is acceptable a plus or minus 2 percent is highly desirable. The mixing of epoxy mortar or grout requires that the epoxy binder thoroughly wet each and every one of the aggregate particles. Although it is difficult, hand mixing in small quantities using a trowel can be accomplished. The prefered method of mixing is by mechanical means. Epoxy concretes are mixed in a similar manner to epoxy mortars except that, in stiff mixes, the large aggregate should be added to the mixed binder first followed by the finer aggregate or sand to help prevent the tendency of the mix to "ball." The finer aggregates should be added slowly. Care should be taken to avoid segregation to obtain a uniform

epoxy concrete. Epoxy grouts or mortars usually consist of four to seven parts of aggregate (by weight) to one part of binder.

The ease and effectiveness of epoxy application is greatly influenced by the temperature of surfaces on which the epoxy compound is applied. Commonly available epoxy compounds in use today react most favorably when temperatures are in the range of 16 to 38° Celsius (60 to 100° Farenheit). If temperatures below 16° Celsius but above 5° Celsius exist, application of epoxy compounds can be accomplished provided a compound is formulated for use within this range and an increased hardening period is not objectionable. At temperatures above 32° Celsius (90° Farenheit) difficulties may be experienced in application owing to acceleration of the reaction and hardening rates.

c. Flexible Joint Requirements.

(1) Why Joints are Necessary. Concrete is normally subject to changes in length, plane or volume caused by changes in its moisture content or temperature, reaction with atmospheric carbon dioxide, or by the imposition or maintenance of loads. The effect may be permanent contractions due to, for example, initial drying shrinkage, carbonation, and irreversible creep. Other effects are cyclical and depend on service conditions such as environmental differences in humidity and temperature or the application of loads and may result in either expansions or contractions. In addition, abnormal volume changes, usually permanent expansions, may occur in the concrete due to sulphate attack, reactions between alkali (from the cement) and certain aggregates, and other causes.

The results of these changes are movements, both permanent and transient, of the extremities of concrete structural units. If, for any reason, contraction movements are excessively restrained, then cracking may occur within the unit. The restraint of expansion movements may result in distortion and cracking within the unit or crushing of its ends and the transmission of unanticipated forces to abutting units. In most concrete structures these effects are objectionable from a structural or an appearance viewpoint. One means of minimizing these effects is to provide joints at which movement can be accommodated without loss of integrity of the structure.

There may be other reasons for providing joints in concrete structures. In many buildings the concrete serves to support or frame curtain walls, cladding, doors, windows, partitions, mechanical and other services. To prevent development of distress in these it is often necessary for them to move to a limited extent independently of overall expansions, contractions and deflections occurring in the concrete. Joints may also be required to facilitate construction without serving any structural purpose.

(2) Why Sealing is Needed. The introduction of joints creates openings which must usually be sealed in order to prevent passage of gases, liquids, or other unwanted substances into the openings or through them. In buildings, it is important to prevent intrusion of wind and rain. In tanks, most canals, pipes, and dams, joints must be sealed to prevent the loss of contents. Moreover, in most structures exposed to the weather the concrete itself must be protected against the possibility of damage from

freezing and thawing, wetting and drying, leaching or erosion caused by any concentrated or excessive influx of water at joints. Foreign solid matter, including ice, must be prevented from collecting in open joints; otherwise the joints cannot close freely later. Should this happen, high stresses may be generated and damage to the concrete may occur.

In industrial floors the concrete at the edges of joints often needs the protections of a filler or sealant (possibly between armored faces) capable of preventing damage from impact of concentrated loads such as steel-wheeled traffic. The specific function of sealants is to prevent the instrusion of liquids (sometimes under pressure), solids or gases, and to protect the concrete against damage. In certain applications secondary functions are to improve thermal and acoustical insulation, damp down vibrations, or prevent unwanted matter collecting in crevices. They must often perform their prime function while subject to repeated contractions and expansions as the joint opens and closes and while exposed to heat, cold moisture, sunlight, and sometimes, aggresive chemicals.

In most concrete structures all concrete-to-concrete joints (contraction, expansion, and construction), and the periphery of openings left for other purposes, require sealing. One exception is contraction joints (and cracks) that have very narrow openings, e.g., those in certain short plain slab or reinforced pavement designs. Other exceptions are certain construction joints, e.g., monolithic joints, not subject to fluid pressure or joints, between precast units used either internally or externally with intentional open draining joints.

d. Types of Joints and Their Function.

(1) Contraction (Control) Joints. These are purposely made planes of weakness designed to regulate cracking that might otherwise occur due to the unavoidable, often unpredictable, contraction of concrete structural units. They are appropriate only where the net result of the contraction and any subsequent expansion during service is such that the units abutting are always shorter than at the time the concrete was placed. They are frequently used to divide large, relatively thin structural units, e.g., pavements, floors, canal linings, retaining and other walls into smaller panels. Contraction joints in structures are often called control joints because they are intended to control crack location.

Contraction joints may form a complete break, dividing the original concrete unit into two or more units. Where the joint is not wide, some continuity may be maintained by aggregate interlock. Where greater continuity is required without restricting freedom to open and close, dowels and in certain cases steps or keyways, may be used. Where restriction of the joint opening is required for structural stability, appropriate tie bars or continuation of the reinforcing steel across the joint may be provided. The necessary plane of weakness may be formed either by partly or fully reducing the concrete cross section. This may be done by installing thin metallic, plastic or wooden strips when the concrete is placed or by sawing the concrete soon after it has hardened.

(2) Expansion (Isolation) Joints. These are designed to prevent the crushing and distortion (including displacement, buckling, and warping)

of the abutting concrete structural units that might otherwise occur due to the transmission of compressive forces that may be developed by expansion, applied loads, or differential movements arising from the configuration of the structure or its settlement. They are frequently used to isolate walls from floors or roofs; columns from floors or cladding; pavement slabs and decks from bridge abutments or piers; and in other locations where restraint or transmission of secondary forces is not desired. Many designers consider it good practice to place such joints where walls change direction as in L-, T-, Y-, and U-shaped structures and where different cross sections develop. Expansion joints in structures are often called isolation joints because they are intended to isolate structural units that behave in different ways.

Expansion joints are made when the concrete is placed, by providing a space between abutting structural units for the full cross section. The space is formed by the use of filler strips of the required thickness or by leaving a gap when precast units are positioned. Provision for continuity or for restricting undesired lateral displacement may be made by incorporating dowels, steps, or keyways.

(3) Construction Joints. These are joints made at the surfaces created before and after interruptions in the placement of concrete or through the positioning of precast units. Locations are usually predetermined by agreement between the engineer and the contractor, so as to limit the work that must be done at one time, with least impairment of the finished structure though joint locations may also be necessitated by unforeseen interruptions in concreting operations. Depending on the structural design they may be required to function later as expansion or contraction joints having the features already described, or they may be required to be monolithic; i.e., the second placement must be soundly bonded to the first so as to maintain complete structural integrity. Construction joints may run horizontally or vertically depending on the placing sequence prescribed by the design of the structure.

(4) Combined and Special Purpose Joints. Construction joints at which the concrete in the second placement is intentionally separated from that in the preceding placement by a bond breaking membrane, but without space to accommodate expansion of the abutting units, also function as contraction joints. Similarly, constrution joints in which a filler is placed, or a gap is otherwise formed by bulkheading or the positioning of precast units, function as expansion joints. Conversely expansion joints are often convenient for forming nonmonolithic construction joints. Expansion joints automatically function as contraction joints, though the converse is only true to an amount limited to the size of gap created by initial shrinkage.

Hinge joints are joints that permit hinge action (rotation) but at which the separation of the abutting units is limited by tie bars or the continuation of reinforcing steel across joints. This term has wide usage in, but is not restricted to, pavements where longitudinal joints function in this manner to overcome warping effects while resisting deflections due to wheel loads or settlement of the subgrade. In structures, hinge joints are often referred to as articulated joints.

Sliding joints may be required where one unit of a structure must move in a plane at right angles to the plane of another unit; e.g., in certain reservoirs where the walls are permitted to move independently of the floor or roof slab. These joints are usually made with a bond-breaking material such as a bituminous compound, paper or felt that also facilitates sliding.

(5) Cracks. Although joints are placed in concrete so that cracks do not occur elsewhere, it is seemingly impossible to prevent occasional cracks between joints for a variety of reasons. As far as the problem of sealing is concerned, cracks may be regarded as contraction joints of irregular line and form.

e. Joint Configurations. Two basic configurations of the schematic joint details for various types of concrete structures occur from the standpoint of the functioning of the sealant. These are known as butt joints and lap joints.

In butt joints, the structural units being joined abut each other and any movement is largely at right angles to the plane of the joint. In lap joints, the units being joined override each other and any relative movement is one of sliding. Butt joints, and these include most stepped joints, are by far the most common. Lap joints may occur in certain sliding joints, between precast units or panels in curtain walls, and at the junctions of these and of cladding and glazing with their concrete or other framing. The difference in the mode of the relative movement between structural units at butt joints and lap joints, in part, controls the functioning of the sealant. In many of the applications of concern pure lap joints do not occur, and the functioning of the lap joint is in practice a combination of butt and lap joint action.

From the viewpoint of the sealant, two sealing systems should be recognized. First, there are open surface joints, as in pavements and buildings in which the joint sealant is exposed to outside conditions on at least one face. Secondly, there are joints such as in containers, dams, and pipelines, in which the primary line of defense against the passage of water is a sealant such as a waterstop or gasket buried deeper in the joint. The functioning and type of sealant material that is suitable and the method of installation are affected by these considerations.

In conclusion, two terms should be mentioned that are in wide, though imprecise use. Irrespective of their type or configuration, joints are often called "working joints" where significant movement occurs and "non-working joints" where movement does not occur or is negligible.

f. Sealant Materials.

(1) Performance in Open Joints. For satisfactory performance a sealant in open surface joints must:

(a) Be an impermeable material;

(b) deform to accommodate the movement and rate of movement occurring at the joint;

(c) sufficiently recover its original properties and shape after cyclical deformations;

(d) remain in contact with the joint faces; (this means that for all sealants, except those preformed sealants that exert a force against the joint face, the sealant must bond to the joint face and not fail in adhesion nor peel at corners or other local areas of stress concentration);

(e) not internally rupture (i.e., fail in cohesion);

(f) resist flow due to gravity (or fluid pressure) or unacceptable softening at higher service temperatures;

(g) not harden or become unacceptably brittle at lower service temperatures; and

(h) not be adversely affected by aging, weathering or other service factors for a reasonable service life under the range of temperatures and other environmental conditions that occur.

(2) Performance Buried In Joints. Sealants buried in joints, such as waterstops and gaskets, generally require similar properties. The method of installation may, however, require the sealant to be in a different form and, because replacement is usually impossible, exceptional durability is required. In addition, depending on the specific service conditions, the sealant may be required to resist one or more of the following: intrusion of foreign material, wear, indentation, pickup, and attack by chemicals. Further requirements may be that the sealant be a specific color, resists change of color, or is nonstaining. Finally, it must not deteriorate when stored for a reasonable time before use. It must be relatively easy to handle and install, and be free of substances harmful to the user and concrete or other material that may abut.

(3) Materials Available. No one material has the perfect properties necessary to fully meet each and every one of the requirements for each and every application. Therefore, it is a matter of selecting from among a large range of materials a particular one that has more of the right properties at the right price to do the job. Table 20 lists commonly used joint sealant materials.

For many years oil-based mastics or bituminous compounds and metallic materials were the only sealants available. In many applications these traditional materials do not perform well and in recent years there has been an active development of "elastomeric" sealants. The behavior of these sealants is largely elastic rather than plastic, and the sealants are flexible rather than rigid at normal service temperatures. Elastomeric materials are available as field-molded and preformed sealants. Though initially more expensive, they may be cheaper in the long run because they usually have a longer service life. Furthermore, these materials can seal joints where considerable movements occur that could not possibly be sealed by the traditional materials.

Table 2[illegible] [illegible] in joints open on at le[illegible] surface.

GROUP	FIELD MOULDED					PREFORMED
TYPE	MASTIC	THERMOPLASTICS		THERMOSETTING		COMPRESSION SEAL
		HOT APPLIED	COLD APPLIED	CHEMICALLY CURING	SOLVENT RELEASE	
Composition	(A) Drying Oils (B) Non-drying Oils (C) Low Melt Point Asphalt (D) Polybutenes (E) Polyisobutylenes or combination of D & E All used with fillers such as asbestos fibre or siliceous materials, all contain [illegible]% solids except D & E which may contain solvent	(F) Asphalts (G) Rubber Asphalts (H) Pitches (I) Coal Tars (J) Rubber Coal Tars All contain [illegible]% solids (W) Hot applied PVC coal tar	(K) Rubber Asphalts (L) Vinyls (M) Acrylics (K) Contains 70 [illegible] solids (L) (M) Contain 75 [illegible] 90% solids [illegible] solvent [illegible] (60 70% solids)	(N) Polysulfide (O) Polysulfide Coal Tar (P) Polyurethane (Q) Polyurethane Coal Tar (R) Silicones (S) [illegible] (N) (R) contain 95 100% solids [illegible] (Q) (S) contain 90 100% solids (P) contains 75 100% solids (N) (P) (R) may be either one or two component system [illegible] (Q) (S) one component system	(T) Neoprene (U) Butadiene Styrene (V) Chlorosulfonated Polyethylene (T) (V) contain 80 90% solids (U) contains 85 90% solids (R) Silicones	(3) Neoprene rubber
Colours	(A) (B) Varied (C) Black only (D) (E) Limited	Black only	[illegible] Black only [illegible] (M) Varied	(N) (R) (S) Varied (O) (P) Limited (Q) Black only	(T) Limited (V) Varied	Black, Exposed surfaces may be treated to give varied colours
Setting or Curing	Non curing [illegible] viscous. A [illegible] form skin on exposed surface	Non curing [illegible] Softens [illegible] (W) Resilient	[illegible] evaporation of water [illegible] for surface skin	Two component system [illegible] One component moisture pickup from the air	Release of solvent	[illegible]
Ageing [illegible] Resistance	Low	Moderate (W) High resistance to weather	Moderate	High	High	High
[illegible] Hardness in Relation to (1) Age	High	High to Moderate (W) No hardness	High	[illegible] High (N) (O) (P) (Q) (R) Moderate	High	Low
or (2) Low temp	High	High to Moderate (W) No hardness	High	(S) (N) (O) (P) (Q) (R) Low	High	Low
Recovery	Low	Moderate (W) High	Low	(N) (O) Moderate (P) (Q) (R) High (S) Low	Low	High
Resistance to Wear	Low	Moderate	Moderate	(P) (Q) (R) (S) High (N) (O) Moderate	Moderate	High
Resistance to Intrusion and Intrusion of Solids	Low	Low at high temperatures (W) High	Low at high temperatures	High	Low	High
Shrinkage after Installation	High	Varies (W) None	High	Low	High	None
Resistance to Chemicals	High except to solvents and fuels	(F) [illegible] High except to solvents and fuels [illegible] High and fuel resistant (W) High	(K) High except to solvents and fuels [illegible] (M) High except [illegible] and [illegible] acids	(N) (P) Low to solvents fuels oxidizing acids (O) (Q) Low to solvents but moderate fuel resistance (R) Low to alkalis (S) High	Low to solvents, fuels and oxidizing acids	High
[illegible] at [illegible]% Elongation	Not applicable	[illegible]	[illegible]	[illegible] (O) (P) (Q) Low (R) High and Low (S) Not applicable	Moderate	[illegible]
Allowable Extension and Compression	±3%	[illegible]% (W) ±25% [illegible]	[illegible]%	[illegible]% [illegible] (S) less	±7%	Must be compressed at all times to 45 85% of its original width
Other Properties	(A) (B) (D) (E) Non staining (D) (E) Pick up dirt use in concealed location only	Due to softening in hot weather usable only in horizontal joints (W) No flow at elevated temperatures	(K) [illegible] [illegible] joints	(N) (P) (R) (S) [illegible]	(U) (V) Non staining (V) Good vapour and dust sealer	
[illegible] first cost	(A) (B) (C) very low (D) (E) Low	(F) [illegible] (J) [illegible] (W) [illegible]	[illegible]	[illegible] (S) [illegible]	(T) (U) (V) Low	(3) High

(4) Field-Molded Sealants. The following types of materials, as listed in Table 20, are currently used as field-molded sealants.

(a) Mastics. Mastics are composed of viscous liquid rendered immobile by the addition of fibers and fillers. They do not usually harden, set, or cure after application, but instead form a skin on the surface exposed to the atmosphere. The vehicle in mastics may include drying or nondrying oils (including oleoresinous compounds), polybutenes, polyisobutylenes, low-melting point asphalts, or combinations of these materials. With any of these, a wide variety of fillers is used, including asbestos fiber, fibrous talc, or finely divided calcareous or siliceous materials. The functional extension-compression range for these materials is approximately ±3 percent.

(b) Thermoplastics, Hot-Applied. These are materials which soften on heating and harden on cooling usually without chemical change. They are generally black and include asphalts, rubber asphalts, pitches, coal tars, and rubber tars. They are usable over an extension-compression range of ±5 percent. This limit is directly influenced by service temperatures and aging characteristics of specific materials. Though initially cheaper than some of the other sealants, their effective life is, in practice, shorter. They tend to lose elasticity and plasticity with age, to accept rather than reject foreign materials, and extrude from joints that close tightly or that have been overfilled. Overheating during the melting process adversely affects the properties of those compounds containing rubber. Those with an asphaltic base are softened by hydrocarbons, such as oil, gasoline, or jet fuel spillage. Tar-based materials are fuel and oil resistant, and these are preferred for service stations, refueling and vehicle parking areas, airfield aprons, and holding pads.

Use of this class of sealants is restricted to horizontal joints since they would run out of vertical joints when installed hot or subsequently in warm weather. They have been widely used in pavement joints, but they tend to be superseded by chemically-curing thermosetting field-molded sealants or compression seals. They are also used in building roof decks and containers.

(c) Thermoplastics, Cold-Applied (solvent or emulsion type). These materials are set either by the release of solvents or the breaking of emulsion on exposure to air. They are sometimes heated to a temperature not exceeding 49^{o} Celsius (120^{o} Farenheit) to facilitate application but are usually handled at ambient temperature. Release of solvent or water can cause shrinkage and increased hardness with a resulting reduction in the joint movement permissible and in serviceability. Products in this category include acrylic, vinyl and modified butyl types which are available in a variety of colors. Their maximum extension-compression range is ±7 percent. Heat softening and cold hardening may, however, reduce this figure. These materials are restricted in use to joints with small movements. Acrylics and vinyls are used in buildings, mainly for calking and glazing. Rubber asphalts are used in canal linings, tanks, and fillers for cracks.

(d) Thermosetting, Chemically Curing Sealants. Sealants in this class are either one or two-component systems which cure by chemical

reaction to a solid state from the liquid form in which they are applied. They include polysulfide, silicone, urethane, and epoxy-based materials. The properties that make them suitable as sealants for a wide range of uses are their resistance to weathering and ozone, flexibility and resilience at both high and low temperatures, and inertness to a wide range of chemicals, including for some, solvents and fuels. In addition, the abrasion and indentation resistance of urethane sealants is above average. Thermosetting, chemically curing sealants have an expansion-compression range up to ±25 percent, depending on the one used, at temperatures from -40^{o} to $+82^{o}$ Celsius (-40^{o} to $+180^{o}$ Farenheit). Silicone sealants remain flexible over an even wider temperature range. They have a wide range of uses in buildings and containers for both vertical and horizontal joints or in pavements. Though initially more expensive thermosetting, chemically curing sealants can stand greater movements than other field-molded sealants, and generally have a much greater service life.

(e) Thermosetting Solvent Release Sealants. Another class of thermosetting sealants is the sealant which cures by the release of solvent. Chlorosulfonated polyethylene and certain butyl and neoprene materials are included in this class and their performance characteristics generally resemble those of thermoplastic solvent-release materials. They are, however, less sensitive to variations in temperature once they have "setup" on exposure to the atmosphere. Their maximum extension-compression range does not, however, exceed ±7 percent. They are mainly used as sealants for calking and joints in buildings; both horizontal and vertical joints have small movements. The cost is somewhat less than that of other elastomeric sealants and the service life is likely to be satisfactory, though for some recent products this has not yet been established by experience.

(f) Rigid. Where special properties are required and movement is negligible, certain rigid materials can be used as field-molded sealants for joints and cracks. These include lead (cool or molten), sulfur, and modified epoxy resins.

f. Preformed Sealants. Preformed sealants (listed in Table 21) may be divided into two classes: rigid and flexible. Most rigid preformed sealants are metallic, such as metal waterstops and flashings. Flexible sealants are usually made from natural or synthetic rubbers, polyvinyl chloride (often called PVC) and like materials, and are used for waterstops, gaskets, and miscellaneous sealing purposes. Preformed equivalents of certain materials, e.g., rubber asphalts, usually categorized as field molded, are available as a convenience to handling and installation.

Compression seals should be included with the flexible group of preformed sealants. However, because their functional principle is different, and because the compartmentalized neoprene type can be used in almost all joint sealant applications as an alternative to field-molded sealants, it is treated separately. Preformed tension-compression seals are also discussed separately.

(1) Rigid Waterstops and Miscellaneous Seals. Rigid waterstops are made of steel, copper and occasionally of lead. Steel waterstops are primarily used in dams and other heavy construction projects. Because ordinary steel may require additional protection against corrosion in dam

Table 21. Preformed materials for waterstops, gaskets, and sealing purposes.[1]

COMPOSITION AND TYPE	PROPERTIES SIGNIFICANT TO APPLICATION	AVAILABLE IN	USES
(1) Butyl · Conventional Rubber Cured	High resistance to water, vapour and weathering. Low permanent set and modulus of elasticity formulations possible, giving high cohesion and recovery. Tough. Colour · Black, can be painted.	Beads, Rods, tubes, flat sheets, tapes and purpose-made shapes	Waterstops, Combined crack inducer and seal. Pressure sensitive dust and water sealing tapes for glazing and curtain walls.
(2) Butyl · Raw, Polymer modified with resins and plasticisers	High resistance to water, vapour and weathering. Good adhesion to metals, glass, plastics. Moldable into place but resists displacement, tough and cohesive. Colour · Black, can be painted.	Beads, tapes, gaskets, grommets.	Glazing seals, lap seams in metal cladding. Curtain wall panels
(3) Neoprene · Conventional Rubber cured	High resistance to oil, water, vapour and weathering. Low permanent set. Colour · basically black but other surface colours can be incorporated.	Beads, rods, tubes, flat-sheets, tapes, purpose-made shapes. Either solid or open or closed cell sponges.	Waterstops, Glazing seals. Insulation and Isolation of service lines. Tension Compression seals. Compression Seals, Gaskets
(4) PVC Polyvinylchloride Thermoplastic, Extrusions or Moldings	High water, vapour, but only moderate chemical resistance. Low permanent set and modulus of elasticity formulations possible, giving high cohesion and recovery. Tough. Can be softened by heating for splicing. Colour · Pigmented black, brown, green, etc.	Beads, rods, tubes, flat sheets, tapes gaskets, purpose-made shapes	Waterstops, Gaskets, Combined crack inducer and seal
(5) Polyisobutylene Non curing	High water, vapour resistance. High flexibility at low temperature. Flows under pressure, surface pressure sensitive, high adhesion, Sometimes used with butyl compounds to control degree of cure. Colour · Black, grey, white	Beads, tapes, grommets, gaskets.	Gaskets, Glazing Seals. Curtain wall panels, Acoustical partitions
(6)a SBR (Styrene Butadiene Rubber) (6)b NBR (Nitrile Butadiene Rubber) Polyisoprene · polydiene · Conventional Rubber cure	High water resistance, NBR has high oil resistance.	Beads, rods, flat sheets tapes, gaskets, grommets, purpose-made shapes. Either solid or cellular sponges.	Waterstops, Gaskets for pipes Insulation and Isolation of Service Lines
(7) Polyurethane, Foam impregnated with polybutylene	Low recovery at low temperature, can be installed in damp joints, Colour · Black, grey	Rods flat sheets (strips) open cell sponges	Gaskets, Compression Seals
(8) Natural Rubber · cured (vulcanized)	High water resistance but deteriorates when exposed to air and sun. Low resistance to oils and solvents. Now largely superseded by synthetic materials, Colour · black	Purpose-made shapes.	Waterstops, Gasket for pipes
(9) Metals (a) Copper (b) Steel (stainless) (c) Lead (d) Bronze	For waterstops: (a) Ductile and Flexible, but work hardens under flexing and fractures. (b) Rigid must be V or U corrgated to accommodate any movement and anchored. (c) Deforms readily but inelastic to deformation under movement.	Flat and preshaped strips. Lead also molten or yarn.	(a) (b) Waterstops (c) Protection for joint edges in floor (d) Panel dividers in floor toppings
(10) Rubber Asphalts	Natural Rubber 8, Butyl 1, or Neoprene 3 digested in asphalt. High viscosity, some elasticity. Moldable into place	Beads, rods, flatsheets (strips) (IIG IIK), Gasket for	As alternative to hot or cold applied Rubber asphalts (IIG IIK), Gasket for pipes

[1]ACI, 1979, Part 3.

construction stainless steels are used to overcome this. They must be low in carbon and stabilized with columbium or titanium to facilitate welding and retain corrosion resistance after welding. Although annealing is required for improved flexibility, the stiffness of steel waterstops may still lead to cracking in the adjacent concrete.

Copper waterstops are used in dams and general construction. They are highly resistant to corrosion, but must be handled with care to avoid damage. For this reason, and because of cost, flexible waterstops are often used instead. Copper is also used for flashings.

Use of lead as waterstops, flashings, or protection in industrial floor joints is now very limited. Bronze strips find wide application in dividing, rather than sealing, terrazzo and other floor toppings into smaller panels.

(2) Flexible Waterstops. The types of materials suitable and in use as flexible waterstops are shown in Table 21. Butyl, neoprene, and natural rubbers have good extensibility and resistance to water or chemicals and may be formulated to give good recovery and fatigue resistance. PVC compounds are, however, probably now the most widely used. While it is not quite as elastic as the rubbers, recovers more slowly from deformation, and is susceptible to degradation by oils, grades with sufficient flexibility (especially important at low temperatures) can be formulated. PVC has the great advantage of being thermoplastic and hence it can easily be spliced on the job or special configurations made for joint intersections. Flexible waterstops are widely used as the primary sealing system in water-containing projects such as dams, tanks, monolithic pipelines, floodwalls, and swimming pools, to keep the water in, and in buildings below grade or in earth-retaining walls to keep the water out.

(3) Gaskets and Miscellaneous Seals. Gaskets and tapes are widely used sealants between glazed surfaces, around windows and other openings in buildings, and at joints between metal or precast concrete panels in curtain walls. Gaskets are also extensively used at joints between precast pipes and where mechanical joints are needed in service lines. The sealing action is obtained either because the sealant is compressed between the joint faces (gaskets) or because the surface of the sealant, as in the case of polyisobutylene, is pressure-sensitive and thus adheres.

(4) Compression Seals. These are preformed compartmentalized or cellular elastomeric devices which, when in compression between the joint faces, function as sealants.

(a) Compartmentalized. Neoprene extruded to the required configuration is currently used for most compression seals. The neoprene formulation used must have special properties for this application. To effectively seal, sufficient contact pressure must be maintained at the joint face. This requires that the seal be in some degree of compression and, for this, good resistance to compression set (i.e., the material must recover sufficiently when released) is required. In addition, the neoprene must be crystallization-resistant at low temperatures (the resultant stiffening may make the seal temporarily ineffective though recovery will

occur on warming). If during the manufacturing process the neoprene is not fully cured, the interior webs may adhere during service (often permanently) when the seal is compressed.

To facilitate installation of compression seals, liquid neoprene-based lubricants are used. For machine installation, additives to make the lubricant thixotropic have been found necessary. Special lubricant adhesives, which both prime and bond, have been formulated for use where improved seal to joint face contact is required.

Neoprene compression seals are effective joint sealants over a wide range of temperatures in most applications. Seals may be used individually, or as components for modular systems.

(b) Modular Systems. In modular systems designed to accommodate larger movements, standard compartmentalized compression seals or rubber tubes are placed between vertical steel I-sections to form modules, each of which can accommodate about 38.1-millimeter (1.5 inch) movement. The complete unit of modules in a series to take the total anticipated movement is supplied prefabricated, ready for installation at the appropriate precompression to suit conditions. A certain amount of out-of-plane movement arising from skew or other causes can be accommodated, and field modifications to allow for unanticipated irreversible opening or closing of the joint can be made by adding or removing seals and separation plates, as required.

Individual seals must remain in at least 15 percent compression at the widest opening. The allowable movement is approximately 40 percent of the uncompressed seal width.

(5) Tension-Compression Seals. One device of this type currently in use consists of neoprene expansive elements combined with encased steel bearing plates and anchorage angles to form a single unit that can be extended or compressed without buckling. Such a unit can support traffic or other loads on its upper surface. Individual units are available in varying lengths up to 1.83 meter (6 feet) and may be butted side by side along the length of the joint opening. The device is bolted directly to the concrete surface at each side of the joint, and this mechanical anchoring permits it to function in tension or compression in response to the movement of the joint.

To date, these devices have been used exclusively on bridge decks, and special sections have been developed to fit curb contours. They may also have application on dam faces or other locations where sealing against considerable pressure and movement is required.

The long-term performance of tension-compression seals remains to be evaluated. Observations of performance indicate that careful installation is important.

9. Repair of Concrete.

a. Evaluation of Damage and Selection of Repair Method. To objectively evaluate the damage to a structure, it is necessary to determine

what caused the damage in the first place. The damage may be the result of poor design, faulty workmanship, mechanical abrasive action, cavitation or erosion from hydraulic action, leaching, chemical attack, chemical reaction inherent in the concrete mixture, exposure to deicing agents, corrosion of embedded metal, or other lengthy exposure to an unfavorable environment. Figures 18 and 19 show damage from various sources.

Whatever may have been the cause, it is essential to establish the extent of the damage, and determine if the major part of the structure is of suitable quality on which to build a sound repair. Based on this information, the type and the extent of the repair are chosen. This is the most difficult step, one which requires a thorough knowledge of the subject and mature judgment by the engineer. If the damage is the result of moderate exposure of what was an inferior concrete in the first place, then replacement by good quality concrete should ensure lasting results. On the other hand, if good quality concrete was destroyed, the problem becomes more complex. In that case, a very superior quality of concrete is required, or the exposure conditions must be altered.

Figure 18. Piles damaged by corrosion of steel reinforcement (photo courtesy of Los Angeles Harbor Department).

Figure 19. Concrete pile damaged by overloading (photo courtesy of Los Angeles Harbor Department).

The repair of spalls from reinforcing bar corrosion requires a more detailed study. Simply replacing the deteriorated concrete and restoring the original cover over the steel will not solve the problem. Also, if the structure is salt-contaminated, the electrolytic conditions will be changed by the application of new concrete, and the consequences of these changed conditions must be considered before any repairs are undertaken.

Basic requirements for achieving a durable repair are:

(1) The repair material must be thoroughly bonded to the sound concrete of the cavity;

(2) the shrinkage of the patch should be small enough not to jeopardize this bond;

(3) the patch and its substrate should be free of cracks;

(4) the response of the patch and the old concrete to changes in temperature, moisture, and load should be similar enough to avoid gross differences in movement;

(5) the patch should be low enough in permeability that moisture will not migrate through it to the old concrete underneath; and

(6) the patch should be resistant to weathering and be durable in the environment in which it is exposed.

b. Types of Repairs.

(1) Concrete Replacement. The concrete replacement method consists of replacing defective concrete with machine-mixed concrete of suitable proportions and consistency, so that it will become integral with the base concrete. Concrete replacement is the desired method if there is honeycomb in new construction or deterioration of old concrete which goes entirely through the wall or beyond the reinforcement, or if the quantity is large. For new work, the repairs should be made immediately after stripping the forms (Tuthill, 1960). Considerable concrete removal is always required for this type of repair. Excavation of affected areas should continue until there is no question that sound concrete has been reached. Additional chipping may be necessary to accommodate the repair method and shape the cavity properly. Although opinions differ on the value of wetting the cavity before placing plastic mortar, most authorities believe it is advisable to keep the faces of the cavity wet for several hours before placing operations are begun. No standing water should be present, however, at the time of placement. Concrete for the repair should generally be similar to the old concrete in maximum size of aggregate and water-cement ratio.

(2) Dry Pack. The dry-pack method consists of ramming a very stiff mix into place in thin layers. It is suitable for filling form tie-rod holes and narrow slots, and for repairing any cavity which has a relatively high ratio of depth to area. Practically no shrinkage will occur with this mix, and it develops a strength equaling or exceeding that of the parent concrete.

(3) Preplaced Aggregate Concrete. Preplaced aggregate concrete may be used advantageously for certain types of repairs. It bonds well to concrete and has low drying shrinkage. It is also well adapted to underwater repairs.

(4) Shotcrete. Shotcrete or gunite has excellent bond with new or old concrete and is frequently the most satisfactory and economical method of making shallow repairs. It is particularly adapted to vertical or overhead surfaces where it is capable of supporting itself (without a form) without sagging or sloughing. Shotcrete repairs generally perform satisfactorily where recommended procedures are followed.

(5) Repair of Scaled Areas and Spalls in Slabs. Scaling of concrete pavement surfaces is not unusual where they are subject to deicing salts, particularly if the concrete is inadequately air-entrained. Such areas may be satisfactorily repaired by a thin concrete overlay provided the surface of the old concrete is sound, durable, and clean. A minimum overlay thickness of about 38 millimeters is needed for good performance The temperature of the underlying slab should be as close as possible to that of the new concrete.

Spalls may occur adjacent to pavement joints or cracks. Spalls usually are several inches in depth, and even deeper excavation may be required to

remove all concrete which has undergone some degree of deterioration. Numerous quick-setting patching materials, some of which are proprietary, are available. Information on the field performance of these materials is given in Federal Highway Administration (1975).

c. Bonding Agents. Bonding agents are used to establish unity between fresh concrete or mortar and the parent concrete. An enriched sand-cement mortar or neat cement paste has generally been used in the past. Epoxy resin is now used frequently as a bonding agent, with the expectation of durable results. This material develops a bond having greater tensile, compressive, and shear strength than concrete. It is waterproof and highly resistant to chemical and solvent action. It is possible to have acceptable results when the concrete is brought to a feather edge; however, better results are obtained if a 25-millimeter-minimum thickness is maintained.

Other types of bonding agents have recently become available. Certain latexes, supplied as an emulsion or dispersion, improve the bond and have good crack resistance. Polyvinyl acetates, stryrenebutadiene, and acrylic are among those used. These materials, particularly the polyvinyl acetates, must be properly compounded if the dried film is to be resistant to moisture. They may be used either as a bonding layer or added to the concrete or mortar mix.

d. Appearance. Unless proper attention is given to all the factors influencing the appearance of concrete repairs, they are likely to be unsightly. In concrete where appearance is important, particular care should be taken to ensure that the texture and color of the repair will match the surrounding concrete. A proper blend of white cement with the job cement is important to come close to matching the color of the original concrete. A patch on a formed concrete surface should never be finished with a steel trowel, since this produces a dark color which is impossible to remove.

e. Curing. All patches (except where epoxy mortar or epoxy concrete is used) must be properly cured t assure proper hydration of the cement and durable concrete or mortar.

f. Treatment of Cracks. The decision of whether a crack should be repaired to restore structural integrity or merely sealed is dependent on the nature of the structure and the cause of the crack, and upon its location and extent. If the stresses which caused the crack have been relieved by its occurrence, the structural integrity can be restored with some expectation of permanency. However, in the case of working cracks (such as cracks caused by foundation movements, or cracks which open and close from temperature changes), the only satisfactory solution is to seal them with a flexible or extensible material.

Thorough cleaning of the crack is essential before any treatment takes place. All loose concrete, oil-based joint sealant, and other foreign material must be removed. The method of cleaning depends on the size of the crack and the nature of the contaminants. It may include any combination of the following: compressed air, wire brushing, sandblasting, routing, or the use of picks or similar tools.

Restoration of structural integrity across a crack has been successfully accomplished using pressure and vacuum injection of low-viscosity epoxies and other monomers which polymerize in situ and rebond the parent concrete. Sealing of cracks without restoration of structural integrity requires the use of materials and techniques similar to those used in sealing joints.

Epoxy resin has become a common and satisfactory material for sealing cracks. The U.S. Navy Civil Engineering Laboratory has developed the following information on these resins. Epoxy, when mixed with a curing agent, becomes epoxy resin, which is a thermosetting plastic that rapidly develops adhesive strength. This synthetic organic compound is stable chemically and physically; it is durable, crack-resistant, and undergoes little reduction in volume (2 to 3 percent) as the result of curing. Adhesives of this type become irreversibly set as the result of exothermic chemical changes initiated by the chemical changes initiated by the chemical curing agent. Epoxy resins can be formulated to have specific values of mechanical and physical characteristics; this is accomplished by means of various hardeners, fillers, flexibilizers, and plasticizers.

Epoxy resin pressure-injected into the cracks of concrete can restore the structure to its original strength. Cracks as narrow as 0.13 millimeter (5 mils) and as wide as 6.35 millimeters (250 mils) can be repaired by injecting epoxy resin. The type of resin needed depends on the width of the crack, on whether the crack is working or stationary, and on the particular method chosen for applying the resin.

Repair of a working crack requires a formulation that will set up rather rapidly so that the bond is not broken before the resin has developed sufficient strength. Narrow cracks require a low-viscosity system to ensure complete penetration of the crack. However, a more viscous system can be used with high-pressure injection methods. The following is a recommended method for repairing cracked concrete by injecting epoxy resin:

(1) Clean the crack with compressed air; remove any salt, oil, or grease deposits from the adjacent concrete surface and, if possible, from the crack itself;

(2) seal the exposed crack along its entire length; (the sealant, which may be an epoxy resin, must be able to withstand internal pressures of at least 862 kilopascals (125 pounds per square inch); if applied to either vertical or overhead cracks, it should be stiff enough so that it will not slough off or sag before hardening; it should be able to bridge cracks as wide as 6.35 millimeters; alternatively, a special thermoplastic sealant tape can be applied directly to the concrete surface and will not deface the concrete when removed later);

(3) if the sealant is an epoxy resin, drill holes about 6.35 millimeters in diameter and about 25.4 millimeters deep along the crack, with spacing of the holes generally not less than the thickness of the concrete member being repaired;

(4) insert metallic nipples in the holes, secured in place with a puttylike epoxy resin sealant, to serve as ports for the epoxy resin;

(5) inject the epoxy resin adhesive under pressure through the first nipple (lowest in the case of a vertical or diagonal crack) until the level of adhesive reaches the next nipple (see Fig. 20);

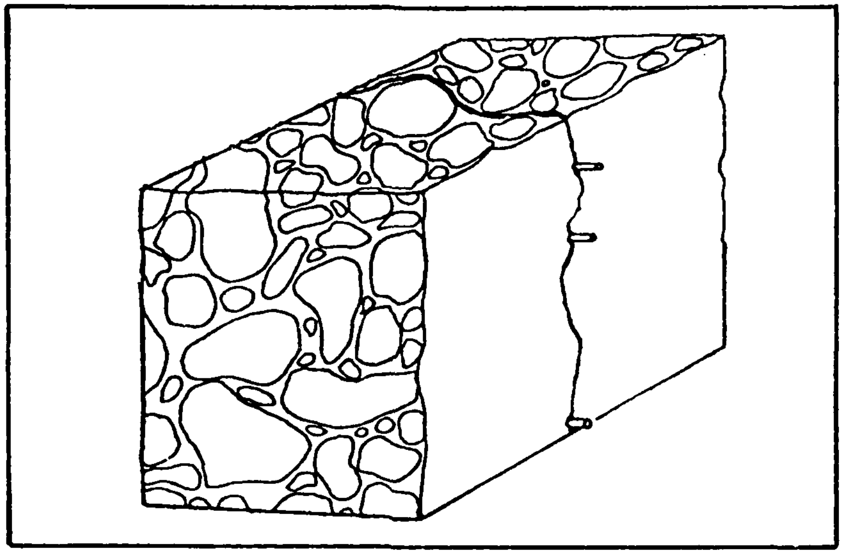


Figure 20. Concrete structure showing nipples through which epoxy resin is injected.

(6) using an inert gas, maintain a pressure of 620 kilopascals (90 pounds per square inch) for about 1 minute to force the adhesive into any interior microcracks adjoining the crack under repair;

(7) release the pressure and then pump more adhesive through the same nipple until the next nipple overflows, then disconnect the hose and cap the nipple;

(8) follow the procedure until the entire crack is filled and all nipples are capped; and

(9) cut off the protruding ends of the capped nipples flush with the concrete surface, plugging the resultant exposed openings with epoxy resin sealant.

g. Repair of Joints. Much experience of poor sealant performance and resulting damage to a wide variety of structures exists. Concern with such problems spurred the development and introduction in the last decade of higher class sealants, both field-molded and preformed. Failures have continued to occur, however, often within days and weeks rather than months or years, for five main reasons:

(1) The joint as designed was of an impossible width, shape or potential movement to seal successfully, yet an attempt was made to seal it;

(2) unanticipated service conditions have resulted in greater joint movements than those allowed for when the joint design and type of sealant were determined;

(3) the wrong type of sealant for the particular conditions was selected, often on the false grounds of economy in first cost;

(4) new sealants have sometimes been initially overpromoted and used before their limitations were realized; and

(5) poor workmanship occurred when constructing the joint, in preparing it to receive the sealant, or during sealant installation.

At joints minor touchup of small gaps and soft or hard spots in field-molded sealants can usually be made with the same sealant. However, where the failure is extensive it is usually necessary to remove the sealant and replace it.

Where the sealant has generally failed but has not come out of the sealing groove it can be removed by hand tools or, on larger projects such as pavements, by routing or plowing with suitable tools. Where widening is required to improve the shape factor, the sealant reservoir can be enlarged by sawing.

After proper preparation to ensure clean joint faces and additional measures designed to improve sealant performance such as the improvement of shape factor, provision of backup material, and possible selection of a better type of sealant, the joint may be resealed.

Minor edge spalls to concrete joint faces may be repaired with an epoxy resin mortar, an essential operation if a compression seal is being used. Otherwise most repairs to correct defects in the original construction of the joint involve major, exacting, and often expensive work. The reason for the failure must be identified and, depending on the cause, continuity must be restored in the joint system either by the removal of whatever is blocking the free working of the joint or by cutting out the whole joint and rebuilding it.

Where cracks have taken over from a nonworking or absent joint, these can be routed out and sealed with a suitable field-molded sealant to prevent damage to the structure. The selection of a suitable sealant and installation method follow those for the equivalent joint. An additional problem occurs where water is flowing through the crack and the upstream face cannot be reached for sealing. Before sealing can be successfully undertaken, the waterflow must be stopped. If the source of water cannot be cut off by dewatering, then (depending on the circumstances) one of the many alternatives such as cutting back the crack deeper and plugging with a quick-setting or dry-pack mortar, or cement, chemical or epoxy resin grouting may be tried. Successful execution of any of these operations usually requires specialized knowledge, experience, and workmanship.

Few exposed sealants have a life as long as that of the structure whose joints they are intended to seal. Fortunately, buried sealants such as waterstops and gaskets have a long life because they are not exposed to weathering and other deteriorating influences.

Most field-molded sealants will, however, require renewal sooner or later if an effective seal is to be maintained and deterioration of the structure is to be avoided. The time at which this becomes necessary is determined by service conditions, by the type of material used, and whether any defects of the kind already enumerated were built in at the time of the original sealing.

10. Delivery and Placement.

a. Batching.

(1) Objectives. During measurement operations aggregates should be handled in a manner to maintain their desired grading, and all materials should be weighted to the tolerances required for desired reproducibility of the concrete mix selected. In addition to accurate weighing another important objective of successful batching is the proper sequencing and blending of the ingredients during charging of the mixers. The final objective is to obtain uniformity and homogeneity in the concrete produced as indicated by such physical properties as unit weight, slump, air content, strength, and air-free mortar content in successive batches of the same mix proportions.

(2) Tolerances. Most engineering organizations, both public and private, issue specifications containing detailed requirements for manual, semiautomatic, and automatic batching equipment for concrete.

(3) Plant Type. Factors affecting the choice of the proper batching systems are (1) size of job, (2) required production rate, and (3) required standards of batching performance. The productive capacity of a plant is determined by a combination of such items as the materials handling system, bin size, batcher size, and plant mixer size and number. The available batching equipment falls into three general categories--manual, semiautomatic, and automatic.

(a) Manual Batching. As the name implies, all operations of weighing and batching of the concrete ingredients are done manually. Manual plants are acceptable for small jobs having low batching rate requirements, generally for jobs up to 3 800 cubic meters (5 000 cubic yards) and rates up to 20 cubic meters per hour (25 cubic yards per hour). As the job size increases, automation of batching operations is rapidly justified. Attempts to increase the capacity of manual plants by rapid batching invariably result in excessive weighing inaccuracies.

(b) Semiautomatic Batching. In this system aggregate bin gates for charging batchers are opened by manually operated pushbuttons or switches. Gates are closed automatically when the designated weight of material has been delivered.

(c) Automatic Batching. Automatic batching of all materials is electrically activated by a single starter switch. Interlocks interrupt

the batching cycle when the scale has not returned to ± 0.3 percent of zero balance or when preset weighing tolerances are exceeded. An individual automatic batching system provides separate scales and batchers for each aggregate size and for each of the other materials batched. The weighing cycle is started by a single starter switch, and individual batchers are charged simultaneously.

b. Mixing.

(1) Total Mixing Water. Uniformity in the measurement of total mixing water involves, in addition to the accurate weighing of added water, control of such additional water sources as mixer wash water, ice, and free moisture in aggregates. One specified tolerance (ASTM Standard C94) for accuracy in measurement of total mixing water, from all sources, is ± 3 percent.

(2) Measurement of Admixtures. Use of admixtures in concrete, particularly air-entraining agents, is a universally accepted practice. Batching tolerance and charging-discharge interlocks should also be provided for admixtures.

(3) Measurement of Materials for Small Jobs. Occasionally the concrete volume on a job is so small, e.g., 76 cubic meters (100 cubic yards) or less, that it is not practical to establish and maintain a batch plant and mixer at the construction site. In this case it is preferable to use ready-mixed concrete or centrally dry-batched materials with truck mixing at the job. If centrally dry-batched concrete is not available, proper precautions should still be taken to properly measure and mix concrete materials. Thorough mixing is essential for the production of uniform concrete. Therefore, equipment and methods used should be capable of effectively mixing concrete materials containing the largest specified aggregate to produce uniform mixes of the lowest slump practical for the work.

c. Transporting.

(1) General Considerations. Concrete can be transported by a variety of methods and equipment, such as truck mixers, stationary truck bodies with and without agitators, buckets hauled by truck or railroad car, pipeline or hose, or conveyor belts. Each type of transportation has specific advantages and disadvantages depending on the conditions of use, mix ingredients, accessibility and location of placing site, required capacity and time for delivery, and weather conditions.

(2) Mixing and Transporting in Revolving-Drum Truck Bodies. Some specifications limit the total drum revolutions that can be used for charging, mixing, agitation, and discharge of concrete in revolving-drum trucks (Fig. 21). Others place limits on the number of revolutions at mixing speed only. A maximum elapsed time of 1.5 hours after the cement has entered the drum until completion of discharge is also frequently specified. Also, provision is made for reduction of the maximum elapsed time in warm weather (ASTM C94-69). Another specification method used is to place no limits on revolutions or elapsed time as long as the specified mixing water is not exceeded, no retempering water is added, the concrete

Figure 21. Concrete delivered by revolving-drum truck (photo courtesy of Los Angeles Harbor Department).

has proper plastic physical properties, and the concrete is of adequate consistency and homogeneity for satisfactory placement and consolidation. This latter approach is favored specifically with regard to maximum allowable time for discharge, and is particularly applicable when cool concrete temperatures are used or when cooler weather prevails. Final determination of whether mixing is being accomplished satisfactorily should be based on standard mixer uniformity tests (ASTM Standard C94-81).

(5) Revolving Drum. By this method, the mixer serves as an agitating transportation unit. The drum is rotated at charging speed

during loading and reduced to agitating speed or stopped after loading is complete. Elapsed time for discharge of the concrete can be the same as for truck mixing.

(4) Final Objective. The method of transportation used should efficiently deliver the concrete to the point of placement without significantly altering its desired properties with regard to water-cement ratio, slump, air content, and homogeneity. Each method of transportation has advantages under particular conditions of use pertaining to such items as mix materials and design, type and accessibility of placement, required delivery capacity, location of batch plant, and others. These various conditions should be carefully reviewed in selecting the type of transportation best suited for economically obtaining quality concrete in-place.

d. Placing Concrete. A basic requirement for placing equipment and methods, as for all other handling equipment and methods, is that the quality of the concrete, in terms of water-cement ratio, slump, air content, and homogeneity, must be preserved. Selection of equipment should be based on its capability for efficiently handling concrete of the most advantageous proportions that can be readily consolidated in place with vibration.

Sufficient placing capacity, as well as mixing and transporting capacity, should be provided so that the concrete can be kept plastic and free of cold joints while it is being placed. It should be placed in horizontal layers not exceeding 0.6 meter (2 feet) in depth, avoiding inclined layers and cold joints. For monolithic construction each concrete layer should be placed while the underlying layer is still responsive to vibration, and layers should be sufficiently shallow to permit knitting the two together by proper vibration. Concrete should be deposited at or near its final position in the placement, eliminating the tendency to segregate when it has to be flowed laterally into place. On sloping surfaces, concrete should be placed at the lower part of the slope first, progressing upward, and thereby increasing natural compaction of the concrete. High-velocity discharge of concrete causing segregation of the concrete should be avoided.

The equipment and method used for placing concrete should avoid separating the coarse aggregate from the concrete. Clusters and pockets of coarse aggregate should be scattered before placing concrete over them to prevent rock pockets and honeycomb in the completed work.

Requests for increases in mixing water are frequently made on the job when concrete of relatively stiff consistency will not flow down chutes, drop out of buckets or hoppers, or discharge through gates or trunks. If the concrete is readily workable and satisfactorily consolidated in place with proper vibration, these requests for additional water are not valid. A limitation on the use of reasonable mix proportions and slump should not be imposed because inadequate placing equipment is being used.

(1) Preplaced Aggregate Concrete. In this method of construction, forms are first filled with clean, well-graded coarse aggregate, and then structural quality grout is injected into the voids of the aggregate mass to produce concrete. It is especially adaptable to underwater construction, to concrete and masonry repairs, and in general to new structures, where placement by conventional means is usually difficult or where concrete

of low volume change is required. As preplaced aggregate concrete construction is of a specialized nature it is advisable that the work be undertaken by qualified personnel experienced in this method of construction. The physical properties of preplaced aggregate concrete are similar to those of conventional concrete; therefore, the same allowable working stresses used for conventional concrete structural design may be used (U.S. Army Engineer Waterways Experiment Station, 1954).

(2) Tremie Concrete. Tremie placement is a method frequently used to place concrete underwater. By the tremie method the concrete is deposited under the surface of fresh concrete previously placed. Placement is usually by gravity feed from above the water surface through a vertical pipe connected to a funnel-shaped hopper at the top (Fig. 22). Tremie concrete flows outward from the bottom of the pipe pushing the existing surface of the concrete outward and upward. As long as flow is smooth so that the concrete surface adjacent to the water is not physically agitated, high-quality concrete will result. Placement can also be carried out through other liquids lighter than concrete such as bentonite slurry to suit special conditions. Tremie concrete is used primarily for cofferdam or caisson seal, underwater structural sections such as bridge piers, drydock walls, floors, etc., and as a seal for precast tunnel sections.

The concrete mix proportions for tremie placement differ from ordinary structural mixes because of the need to have the mix flow into place slowly by gravity without vibration or mechanical help. The mix should be proportioned for a slump 15 to 23 centimeters (6 to 9 inches). It is generally preferable to use a natural round gravel rather than crushed rock because of flow requirements. The maximum size aggregate is usually 38.1 millimeters. However, a nominal size of 19.0 millimeters or 9.51 millimeters (3/4 or 3/8 inch) can be used for complex sections and critical flow conditions. The proportion of fine aggregate (sand) is usually in the range of 40 to 50 percent of the total weight of aggregate. Water-reducing retarding admixtures conforming to ASTM Standard C494 have been found to be an aid in placement of the concrete, and the retarding effect slows the rate of heat development and provides flatter slopes with less laitance (Williams, 1959). Air-entraining admixtures and pozzolans are also beneficial to flow characteristics. The concrete temperatures should be kept as low as practical, usually below 21.1^{o} Celsius to improve placement and structural qualities. The recommended maximum water-cement ratio for concrete deposited by tremie under water is 0.44 by weight.

The compressive strength of rich, high-slump tremie concrete mixes will often be approximately 28 to 56 megapascals per square meter (4 000 to 8 000 pounds per square inch) at 28 days. Curing conditions are excellent and shrinkage is low. The surfaces that will be in contact with the concrete should be free of mud, marine growth, sewage, and other matter. Bond to clean surfaces of steel, rock, and timber is generally excellent. The heat of hydration developed in rich mixes produces high early strength even when water temperature is as low as 4.4^{o} Celsius (40^{o} Fahrenheit). When large masses of tremie concrete are placed, volume change due to heat development may warrant special consideration. The use of suitable instrumentation may be required to monitor the temperature rise in these structures.

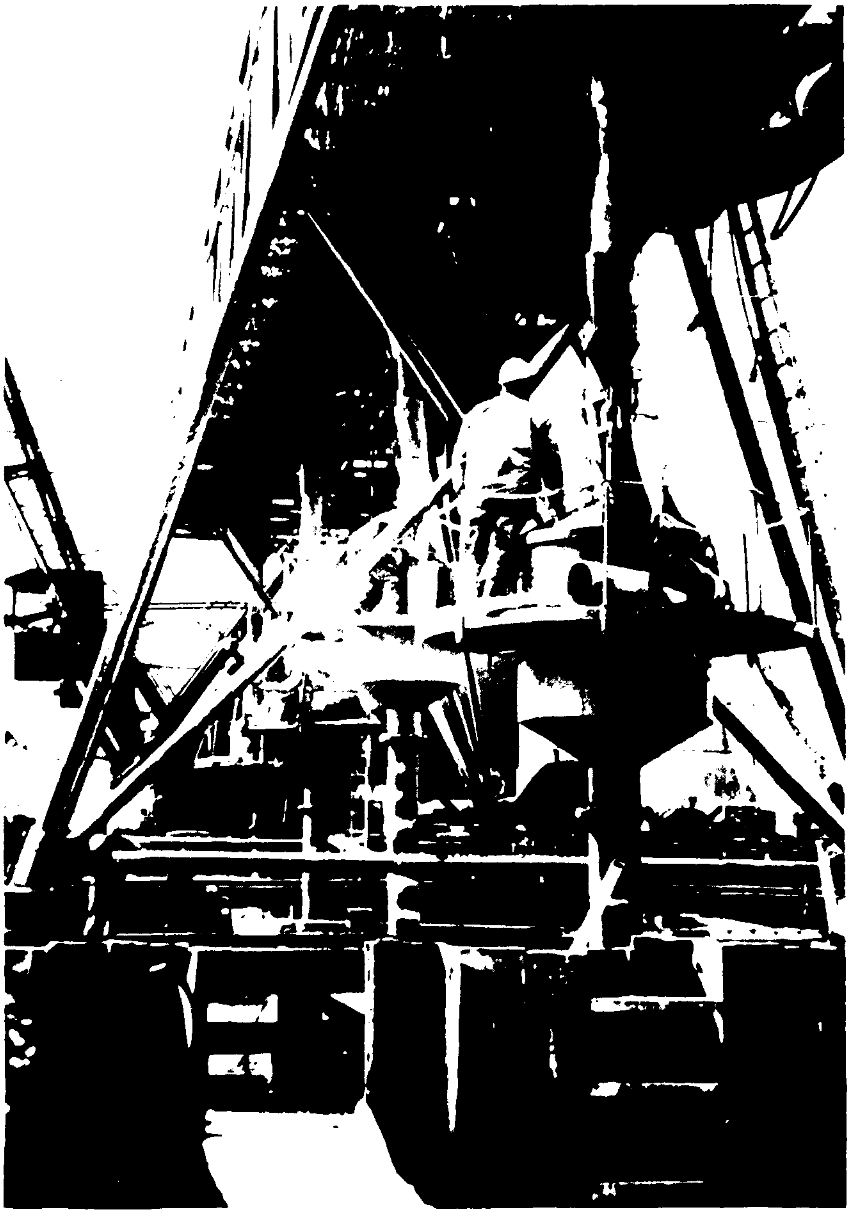


Figure 22. Tremies in place before pouring.

(3) Pumping. Pumped concrete may be defined as concrete conveyed by pressures through either rigid pipe or flexible hose and discharged directly into the desired area (Fig. 23). Pumping may be used for most concrete construction, but is especially useful where space or access of construction equipment is limited. Most concrete transported to the placement areas by pumping methods is pumped through a rigid pipe or a combination of rigid pipe and heavy-duty flexible hose. Effective pumping range will vary from 90 to 305 meters (300 to 1 000 feet) horizontally or 30 to 90 meters vertically.

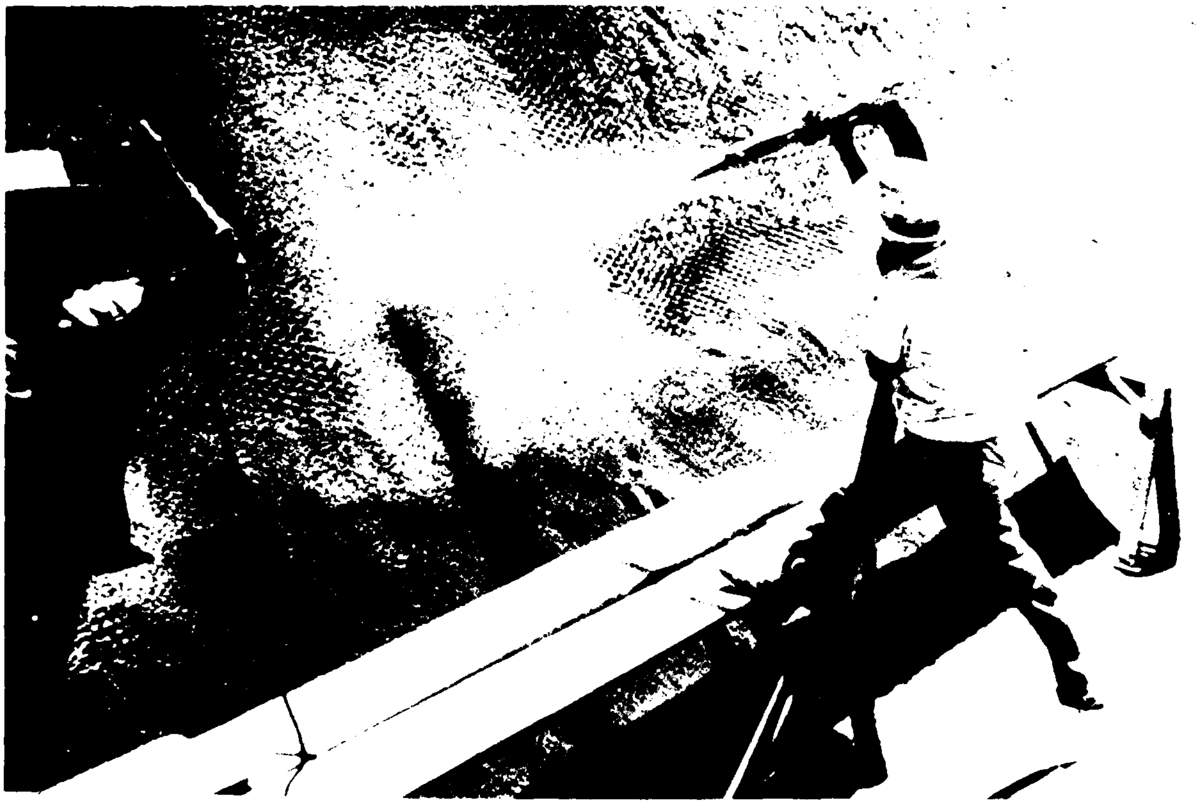


Figure 23. Pumped concrete applied with a pressure nozzle.

To establish the optimum slump for a pump mix and to maintain control of that particular slump through the course of the job are both extremely important factors. Experience indicates that slumps below 50 millimeters (2 inches) are impractical for pumping, and slumps above 152 millimeters (6 inches) should be avoided. In mixtures with high slump, the aggregate will separate from the mortar and paste and may cause blocking in the pump line. Overly wet mixes also bleed and increase shrinkage. It is more important to obtain a truly plastic mix through proper proportioning than to try to overcome deficiencies by adding more mortar.

11. Environmental Considerations.

The following environmental features are generally to be considered in the use of concrete in coastal structures. Portland cement concrete is a durable material and well suited to use in the coastal environment. When properly designed, placed and cured, it will resist most coastal environments for many years.

a. Corrosive and Pollutant Attacks on Exposed Surfaces. Concrete is rarely attacked by solid, dry chemicals. In order to significantly attack concrete, corrosive chemicals must be in solution form and above some minimum concentration. Chemical attack on concrete is generally the

result of exposure to sulfates or acids. Natural-occurring sulfates of sodium, potassium, calcium, or magnesium, which are sometimes in soil or dissolved in ground water adjacent to concrete structures, can attack concrete.

There are two chemical reactions likely to be involved in sulfate attack on concrete: (1) the combination of sulfate with free calcium hydroxide liberated during the hydration of the cement to form calcium sulfate (gypsum), and (2) the combination of gypsum and hydrated calcium aluminate to form calcium sulfoaluminate.

The effects of some of the more common chemicals on the deterioration of concrete are indicated in Table 22. Many pollutants contain the chemicals indicated in the table.

b. Sunlight Exposure Effects. Sunlight has virtually no effect on the deterioration of concrete.

c. Water Penetration Effects. Pure water does not attack concrete, but it can be the medium for dissolving most chemicals, which in solution may cause concrete deterioration. Seawater has a high sulfate and chloride content which may be only moderately aggressive to concrete; however, if these chemicals can penetrate the concrete to the steel reinforcing then rapid deterioration will occur.

d. Wave and Current Effects. Waves and currents have no direct effect on concrete or are not the direct cause of its deterioration. Concrete destruction only occurs when the structure is not adequately designed. Wear to concrete structures does occur because of cavitation occurring as a result of the collapse of bubbles of water vapor. Concrete wear by abrasion may also occur as a result of solid particle (such as sand) transported by waves and currents impinging on a concrete surface.

e. Effect of Severe Temperature and Ice. Resistance to severe temperature changes in concrete are more a function of proper mix design with good aggregate and proper curing than any other factors. Generally, high temperatures do not affect well-cured concrete. Building codes generally require concrete to resist heat of 538^{o} Celsius (1 000^{o} Farenheit) for 5 minutes to more than 1 038^{o} Celsius (1 900^{o} Farenheit) for 3 hours, depending on the thickness of concrete tested. Sustained high-ambient temperatures (above 200^{o} celsius) will stop normal crystal growths in concrete and normal strength gain with aging.

To provide a high degree of resistance to the disruptive action of freezing and thawing and of deicing chemicals air-entraining admixtures are used. Unless low temperatures are very extreme, properly designed concrete will not deteriorate or spall in freezing conditions.

f. Marine Organisms. Marine organisms do not injure good concrete, containing sound aggregate. For example, concrete which is composed of siliceous aggregates is resistant to marine borer activity because the material is extremely abrasive to the lime shells of boring organisms. However, in tropical and semitropical water there have been instances of borer damage in concretes where limestone or similar sand has been used.

Table 22. Effect of commonly used chemicals on concrete.

Rate of attack at ambient temperature	Inorganic acids	Organic acids	Alkaline solutions	Salt solutions	Miscellaneous
Rapid	Hydrochloric Hydrofluoric Nitric Sulfuric	Acetic Formic	--	Aluminum chloride	--
Moderate	Phosphoric	Tannic	Sodium hydroxide- > 20 pct[1]	Ammonium nitrate Ammonium sulfate Sodium sulfate Magnesium sulfate Calcium sulfate	Bromine (gas) Sulfite liquor
Slow	Carbonic	--	Sodium hydroxide 10 to 20 pct[1] Sodium hypochlorite	Ammonium chloride Magnesium chloride Sodium cyanide	Chlorine (gas) Seawater Softwater
Negligible	--	Oxalic Tartaric	Sodium hydroxide < 10 pct[1] Sodium hypochlorite Ammonium hydroxide	Calcium chloride Sodium chloride Zinc nitrate Sodium chromate	Ammonia (liquid)

[1]Avoid siliceous aggregates because they are attacked by strong solutions of hydroxide.

The first record of marine animals entering concrete is found in Hill and Kofoid (1927). This record indicated that Pholadidae were found drilling into concrete jackets used to protect wood piles from attacks by *Limnoria* and *Teredo*. Subsequent tests showed that the mortar jackets bore no resemblance to even a poor grade of structural concrete and offered no resistance to the boring mechanisms of Pholads.

While mollusks have been found in lightweight mortar pontoons, of dubious quality, additional tests prove that Pholads could not enter any material harder than their shells (about 2.5 on the diamond scale).

g. Periodic Wetting and Drying. Periodic wetting and drying may cause the formation on the concrete surface of "D cracks" (the progressive formation of fine cracks, often in random pattern). Such cracks may enlarge in time and if exposed to freezing and thawing can result in concrete spalling.

h. Wind Erosion. Concrete resistance to wind is usually not a serious problem in coastal structures. Where strong winds may pick up sand particles, causing some etching of concrete surfaces similar to surf zone abrasion (usually near the ground line), it would take many years of exposure to structural grade concrete for wind erosion to become a problem.

i. Effects of Burrowing Animals. Marine animals do not penetrate good concrete as indicated in paragraph (f) above and the larger dryland animals do not attack concrete. Concrete is one of the hardest materials in the coastal environment and contains no food value for such animals.

j. Effects of Flora. There are no reported effects of flora growth on concrete.

k. Fire. Concrete resistance to fire or extreme high temperatures is stated in paragraph (e) above.

l. Abrasion. Abrasion is defined as the ability of a surface to be worn away by rubbing and friction. Wind- or water-borne particles can abrade or etch concrete surfaces. If windborne particles cause abrasion, some dusting problem could develop; however, the slow rate of the abrasion process in the coastal zone is usually unnoticeable. Wear on concrete structures exposed to high velocities and negative pressures is generally known as cavitation erosion. Precise limits for abrasion resistance of concrete are not possible. It is necessary to rely on relative values based on weight or volume loss, depth of wear, or visual inspection.

m. Seismic Effect. Severe seismic forces can cause failure of a concrete structure directly or by altering the foundation on which the structure rests such that subsequent settlement can result in structural failure or deterioration. With proper design concrete can be made to resist seismic effects.

n. Human Activity. Human activity has very little impact on concrete structures except where visual impact may be noticeable by graffiti or other defacing actions.

12. Use in Coastal Structures.

a. General. Concrete is easily adapted to coastal construction in that local aggregates are normally available at or near the site with the only import materials being cement and steel reinforcing. It can be cast in most any shape or size to fit site requirements and the structures can be built in sections either by casting separate members and assembling in place to create a large structure or as mass concrete placed a section at a time to produce a large continuous structure. This characteristic allows the design engineer a wide selection of type, size and configuration of structure design. The excellent physical and strength properties of

concrete as well as its stability and resistance to the environment make it an ideal coastal zone construction material. However, concrete being a relatively heavy material is limited in its use where its heavy weight may be a deterrent.

In addition to structures constructed totally of concrete, many concrete structural elements are used in a variety of coastal projects, such as armor units of various shapes and size, concrete caissons, solid and perforated blocks, sheet and bearing piles, and beams and slabs. Floating structures such as caissons, barges, and pontoons have been successfully built and used. Concrete is also used unreinforced in mass structures. Reinforced and prestressed units are usually precast structure elements.

b. Seawalls, Bulkheads, and Revetments. Seawalls, bulkheads and revetments are distinguished by purpose. In general, seawalls are the most massive of the three structures, because they resist the force of the waves. Bulkheads are next in size. Their function is to retain fill; they are generally not exposed to severe wave action. Revetments are the lightest, because they are designed to protect shorelines against erosion by currents or light wave action.

(1) Seawalls. A curved-face seawall and a combination stepped and curved-face seawall are usually massive structures which are built to resist high wave action and reduce scour. Figure 24 shows an example of reinforced concrete curved surface seawall. The stepped seawall was designed for stability against moderate waves.

(2) Bulkheads. Concrete bulkheads can take virtually any form or configuration required for the intended use and location.

(3) Revetments. Structural types of revetments used for coastal protection in exposed and sheltered areas are illustrated in Figures 25, 26, and 27. There are two types of revetments: the rigid, cast-in-place concrete type (Fig. 25) and the flexible or articulated armor unit type (Figs. 26 and 27). A rigid concrete revetment provides excellent bank protection, but the site must be dewatered during construction to pour the concrete. A flexible structure also provides excellent bank protection, and can tolerate minor consolidation or settlement without structural failure. The articulated block structure in Figure 27 allows for the relief of hydrostatic uplift pressure generated by wave action.

Interlocking concrete blocks have been used extensively for shore protection in the Netherlands and England, and have become popular in the United States. Typical blocks are generally square slabs with shiplap-type interlocking joints (Fig. 27). The joint of the shiplap type provides a mechanical interlock with adjacent blocks. Stability of an interlocking concrete block depends largely on the type of mechanical interlock. Concrete piles are sometimes used as cutoff walls for revetments and seawalls. Concrete foundation piles are sometimes used to support seawalls and other massive concrete structures, such as caisson breakwaters.

c. Groins. Concrete groins are built of concrete sheet piles or king piles and panels if they are impermeable. The piles are usually prestressed units and tied together with a cast-in-place concrete cap. If greater pile

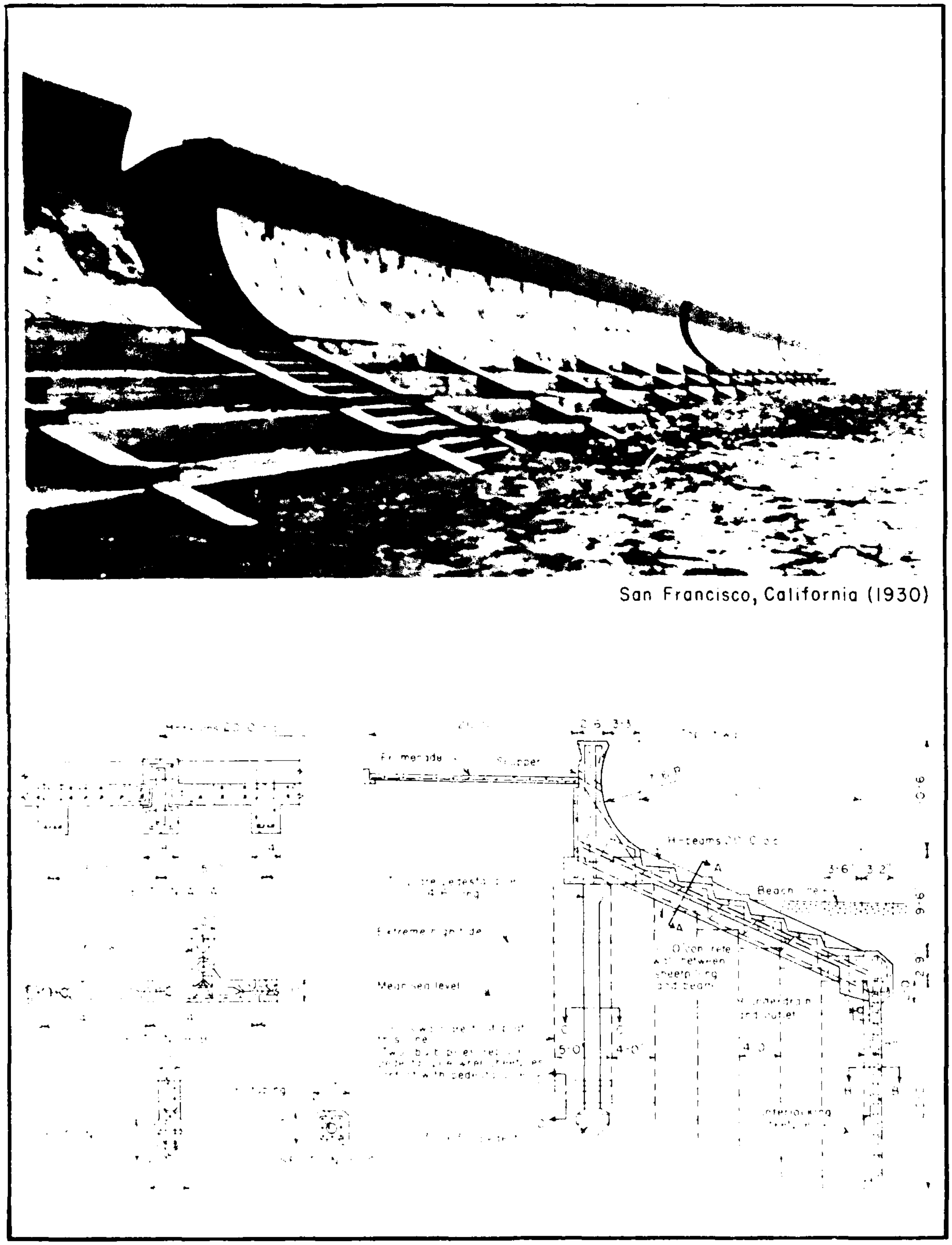


Figure 24. Concrete combination stepped and curved-face seawall (U.S. Army, Corps of Engineers, CERC, 1977).

Pioneer Point, Cambridge, Maryland (before 1966)
Courtesy of Portland Cement Association

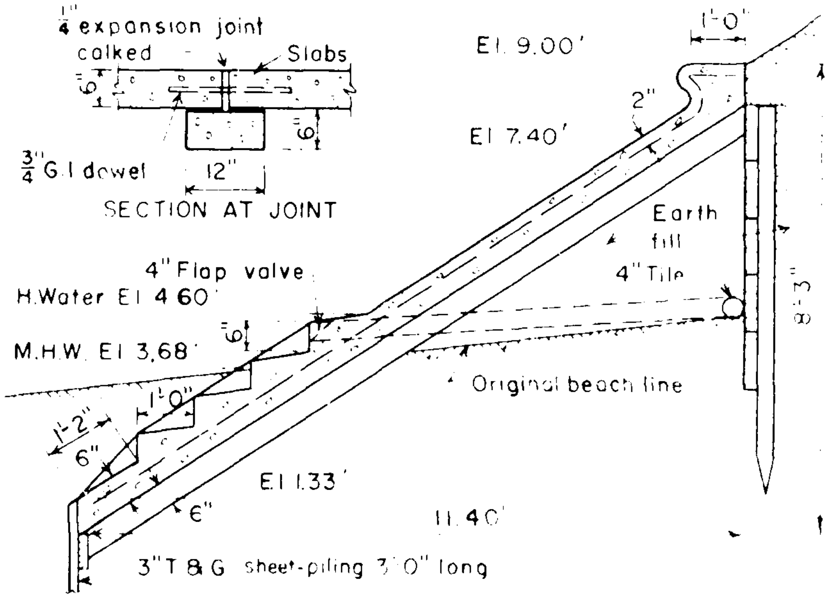


Figure 25. Concrete revetment (U.S. Army, Corps of Engineers, CERC, 1977).

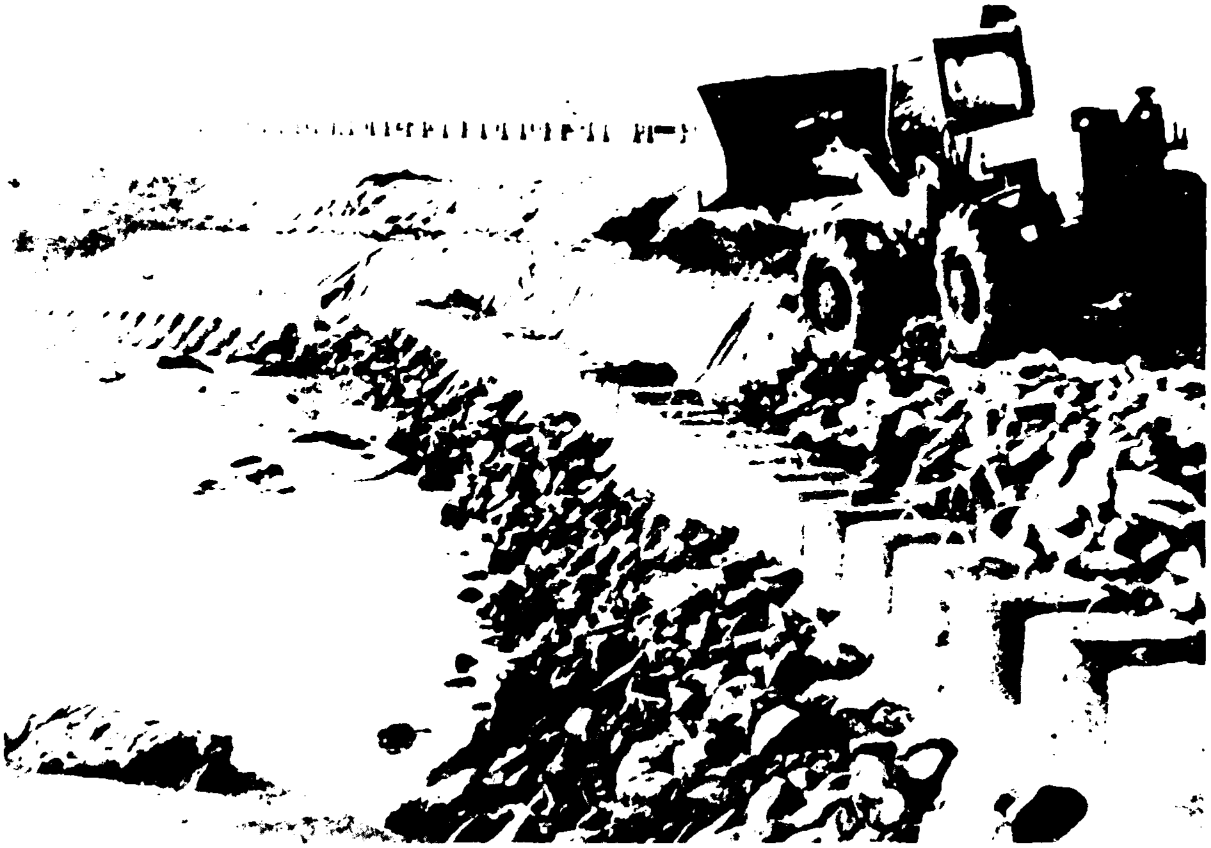
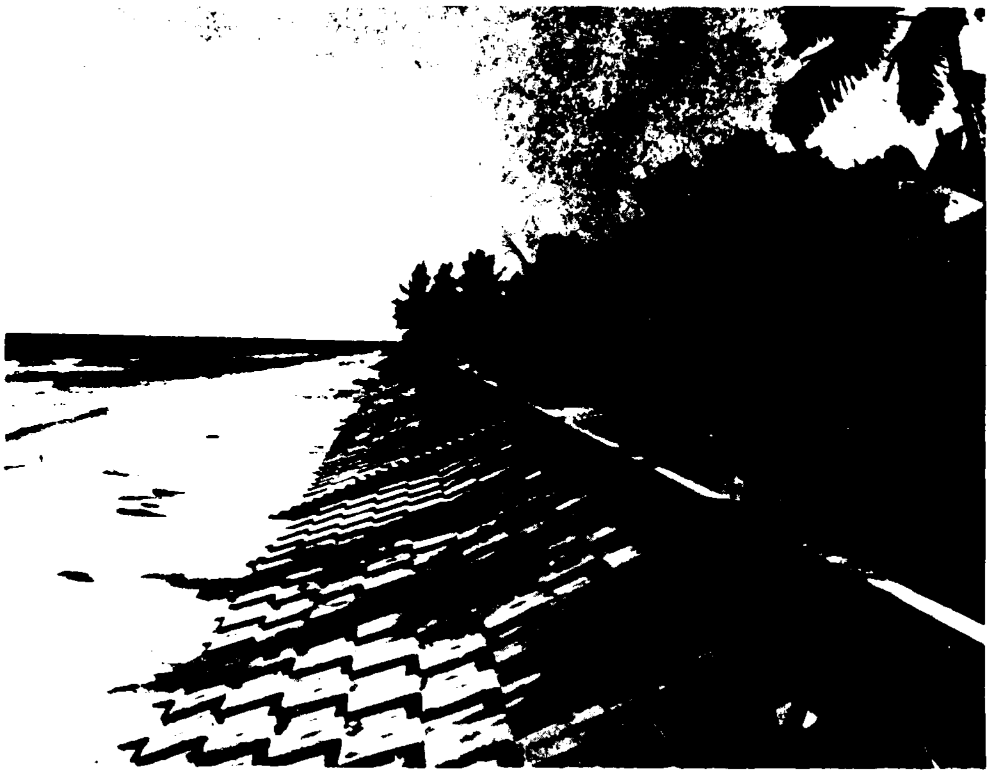


Figure 26. Articulated armor unit revetment (photo courtesy of Marine Modules Inc.).

flexibility is required, timber wales have been used. Permeable-type concrete groins have been built in the past that permitted the passage of sand through the structure but are not used at present. In low wave climates grout-filled bags are also used as an installation convenience; the bags, usually plastic, deteriorate leaving the small concrete shapes as protection of the groins.

d. Jetties and Breakwaters. In exposed locations, jetties and breakwaters are generally some variation of a rubble-mound structure containing concrete either as a binding material to hold rock together or as separate elements of breakwaters having a heavy weight as well as energy absorption characteristics. Some types of jetties are illustrated in Figures 28 and 29. In less severe exposures, both cellular steel and concrete caissons have been used. In low wave climates grout filled bags are used.

Where rock armor units in adequate quantities or size are not economically available, concrete armor units are used. Also, concrete sheet piles are sometimes used as core for jetties. Figure 30 illustrates the use of Quadripod armor units on the rubble-mound jetty at Santa Cruz, California. Figure 29 illustrates the use of the more recently developed dolos armor unit where 374- and 383-kilonewton (42 and 43 ton) dolosse were



Jupiter Island, Florida (1965)
Courtesy of Carthage Mills Inc.
Erosion Control Division

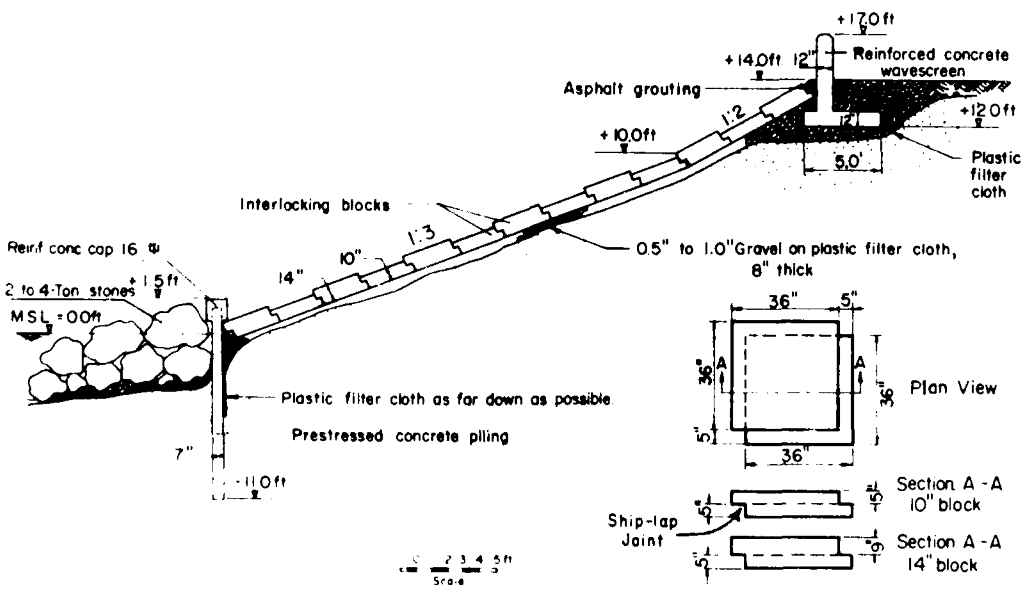


Figure 27. Interlocking concrete block revetment
(U.S. Army, Corps of Engineers, CERC, 1977).

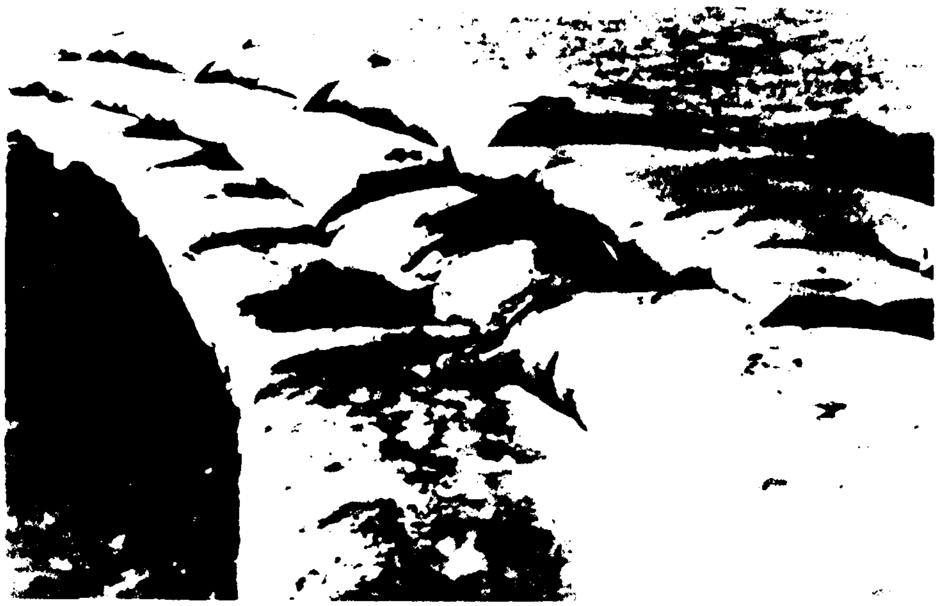


Figure 28. Fabric tubes filled with concrete form a jetty (photo courtesy of Fabriform).

used to rehabilitate the seaward end of the Humboldt Bay jetties against 12-meter (40 foot) breaking waves (Magoon and Shimizu, 1971).

(1) Concrete Caisson Breakwater. Breakwaters of this type are built of reinforced concrete shells that are floated into position, settled on a prepared foundation, filled with stone or sand for stability, and then capped with concrete or stones. These structures may be constructed with or without parapet walls for protection against wave overtopping. In general, concrete caissons have a reinforced concrete bottom, although open-bottom concrete caissons have been used. The open-bottom type is closed with a temporary wooden bottom that is removed after the caisson is placed on the foundation. The stone used to fill the compartments combines with the foundation material to provide additional resistance against horizontal movement.

Figure 31 illustrates a patented perforated type of caisson breakwater (Jarlan, 1961). The installation at Baie Comeau, Quebec (Stevenston, 1963), utilized the caisson as a wharf on the harborside. The holes or perforations on the seaward side reduce the undesirable conditions of a smooth vertical face wall and are an illustration of complex structural shapes possible because of the way concrete is cast.

(2) Concrete Armor Units. Many different concrete shapes have been developed as armor units for rubble structures. The major advantage of concrete armor units is that they usually have a higher stability coefficient value, thus permitting the use of steeper structure side slopes or a lighter weight of armor unit. This property is especially valuable when quarrystone of the required size is not available.

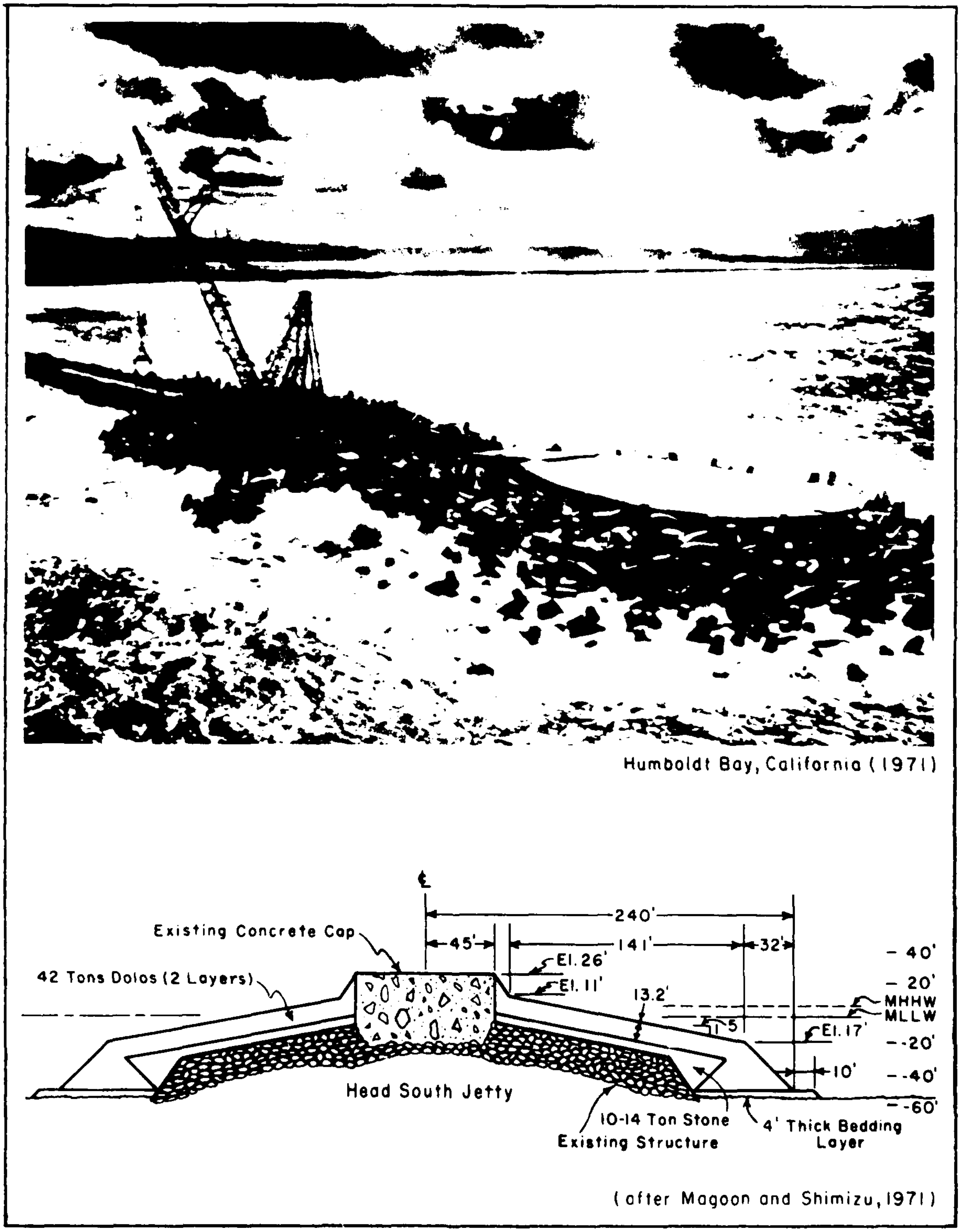


Figure 29. Dolos rubble-mound jetty (U.S. Army, Corps of Engineers, CERC, 1977).

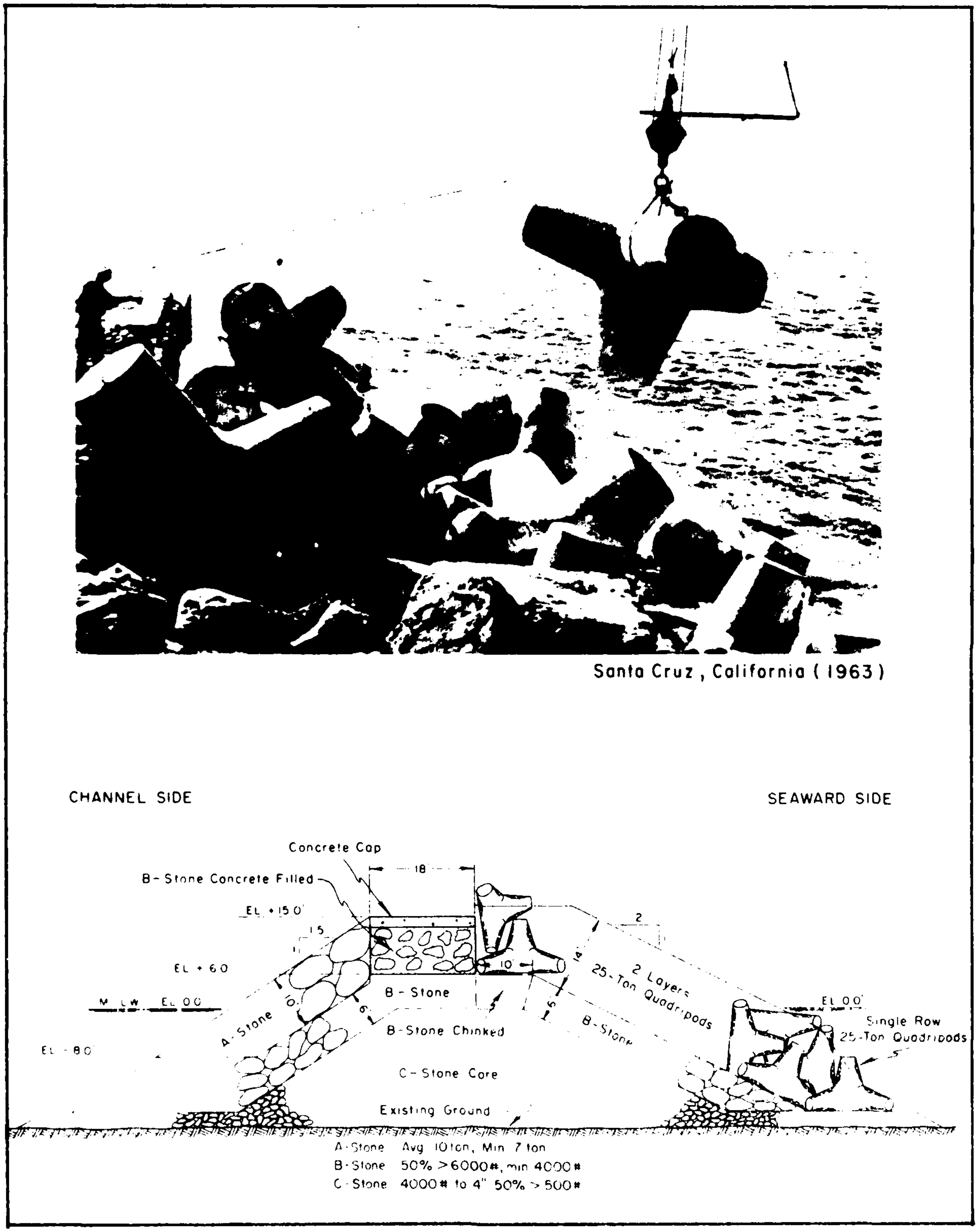
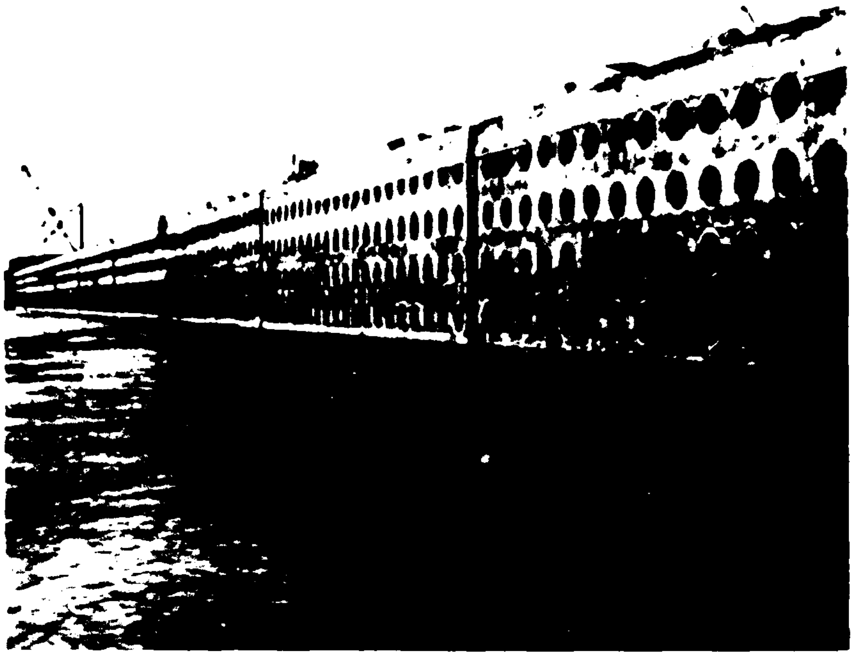


Figure 30. Quadripod rubble-mound jetty (U.S. Army, Corps of Engineers, CERC, 1977).



Baie Comeau, Quebec, Canada (August 1962)

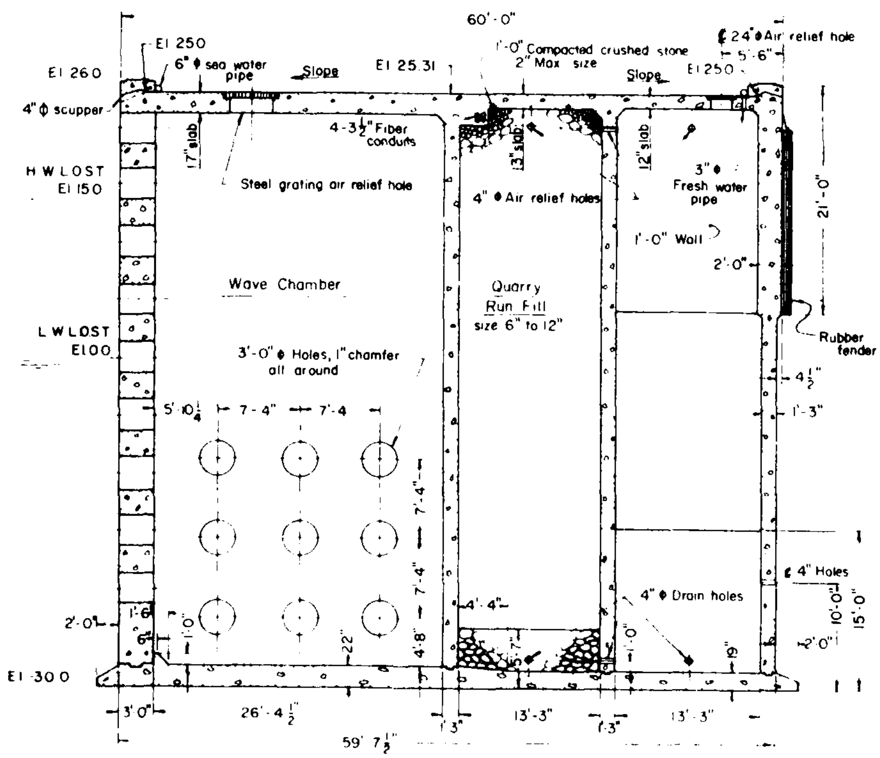


Figure 31. Perforated caisson breakwater (U.S. Army, Corps of Engineers, CERC, 1977).

The unit weight of concrete containing normal aggregates will range from 22.0 to 24.3 kilonewtons per cubic meter (140 to 155 pounds per cubic foot) but can be increased with the use of heavy aggregate to 28.3 (180 pounds per cubic foot) usually at some additional cost. The technique of placement and the size of the armor unit will determine if reinforcing is required in dolos or tribar units. Heavy units, exceeding about 178 kilonewtons (20 tons) will require reinforcing if placed from a landside unit. Placing armor units from floating equipment where the wave action may cause bumping of the units may require reinforcing in armor units as light as 89 kilonewtons (10 tons).

Table 23 lists the concrete armor units in use today and shows where and when the unit was developed. Table 24 lists projects using tetrapods, tribars, quadripods, and dolosse in the United States. Commonly used types of units are illustrated in Figure 32.

e. Other Structures. Concrete has been adopted to many kinds of marine structures as monolithic or cast-in-place structures as well as precast or prestressed units. Concrete is an optimum material for marine structures as it combines durability, strength, and economy. The ability to produce concrete in most any geometric form gives it a high adaptability to most any location and condition of use required.

(1) Navigation Structures. Prestressed concrete piles are used for navigation light standards. Navigation aids located on breakwaters, along the shoreline as lighthouses and radio signal towers are usually of concrete construction. Also included as navigation structures are mooring anchors for bouys of all kinds.

(2) Piers and Wharves. Concrete is the most used construction material in building piers and wharves located either on the coastline or in protected harbors. All the elements of pier construction such as piles, dock units, pier girders, substructures, or bulkheads are built of concrete or a combination of concrete and wood or steel. Even then concrete may be used to protect the wood or steel from erosion, corrosion, dryrot, or marine organisms attack. Figures 33 to 36 are examples of commercial concrete structures located on the coastline. Special piers have been constructed for product loading lines, waste water disposal, and other discharge lines. Figure 37 shows the piling and deck structure of a recreation pier extending from shore to the open ocean. There are, of course, innumerable concrete piers and wharves constructed in bays and protected harbors along the world's shoreline.

The use of concrete in these structures is most feasible because it is durable, is readily available in most locations, can be produced in virtually any size or shape, and is economical. Recent developments in precast and prestressed concrete units provide a means of fast and simplified construction procedures with the final structure being both stable and durable.

Concrete piling is easily manufactured in most any length to about 36 meters (118 feet), although longer piles have been made and commonly in round, square, octagonal or hollow core cross sections. Either reinforced or prestressed concrete piles can be designed to support very heavy loads.

Table 23. Typical concrete armor units in use today.

Name of Unit	Development of Unit	
	Country	Year
Accropode	France	1978
Antifer	Netherlands	1978
Cube[1,2]	-	-
Cube (modified)[1]	United States	1959
Dolos[1]	South Africa	1963
Handbar	Australia	1979
Hexapod[1]	United States	1959
Quadripod[1]	United States	1959
Rectangular Block[1,2]		
Stabit	England	1961
Tetrahedron (perforated)[1,3]	United States	1959
Tetrapod	France	1950
Tribar[1]	United States	1958

[1]The units have been tested, some extensively, at the Waterways Experiment Station (WES).

[2]Cubes and rectangular blocks are known to have been used in masonry-type breakwaters since early Roman times, and in rubble-mound breakwaters during the last two centuries. The cube was tested at WES as early as 1943.

[3]Solid tetrahedrons are known to have been used in hydraulic works for many years. This unit was tested at WES in 1959.

Table 24. Concrete armor projects in the United States.

Date	Location	Structure	Armor Unit
1956	Crescent City, Calif.	Breakwater	25-ton tetrapods
1957	Kahului, Hawaii	Breakwater	33-ton tetrapods
1958	Nawiliwili, Hawaii	Breakwater	18-ton tribars
1958	Rincon Island, Calif.	Revetment	31-ton tetrapods
1963	Kahului, Hawaii	Breakwater	19- to 50-ton tribars
1963	Santa Cruz, Calif.	Breakwater	28-ton quadripods
1963	Ventura, Calif.	Jetty	10.7-ton tribars
1971	Diablo Canyon, Calif.	Breakwater	21.5- to 36.5-ton tribars
1971	Humboldt Bay, Calif.	Jetty	42- to 43-ton dolosse
1973	Crescent City, Calif.	Breakwater	40-ton dolosse
1980	Cleveland Harbor, Ohio	Breakwater	2-ton dolosse
1982	Manasquan Inlet, N.J.	Jetty	16-ton dolosse

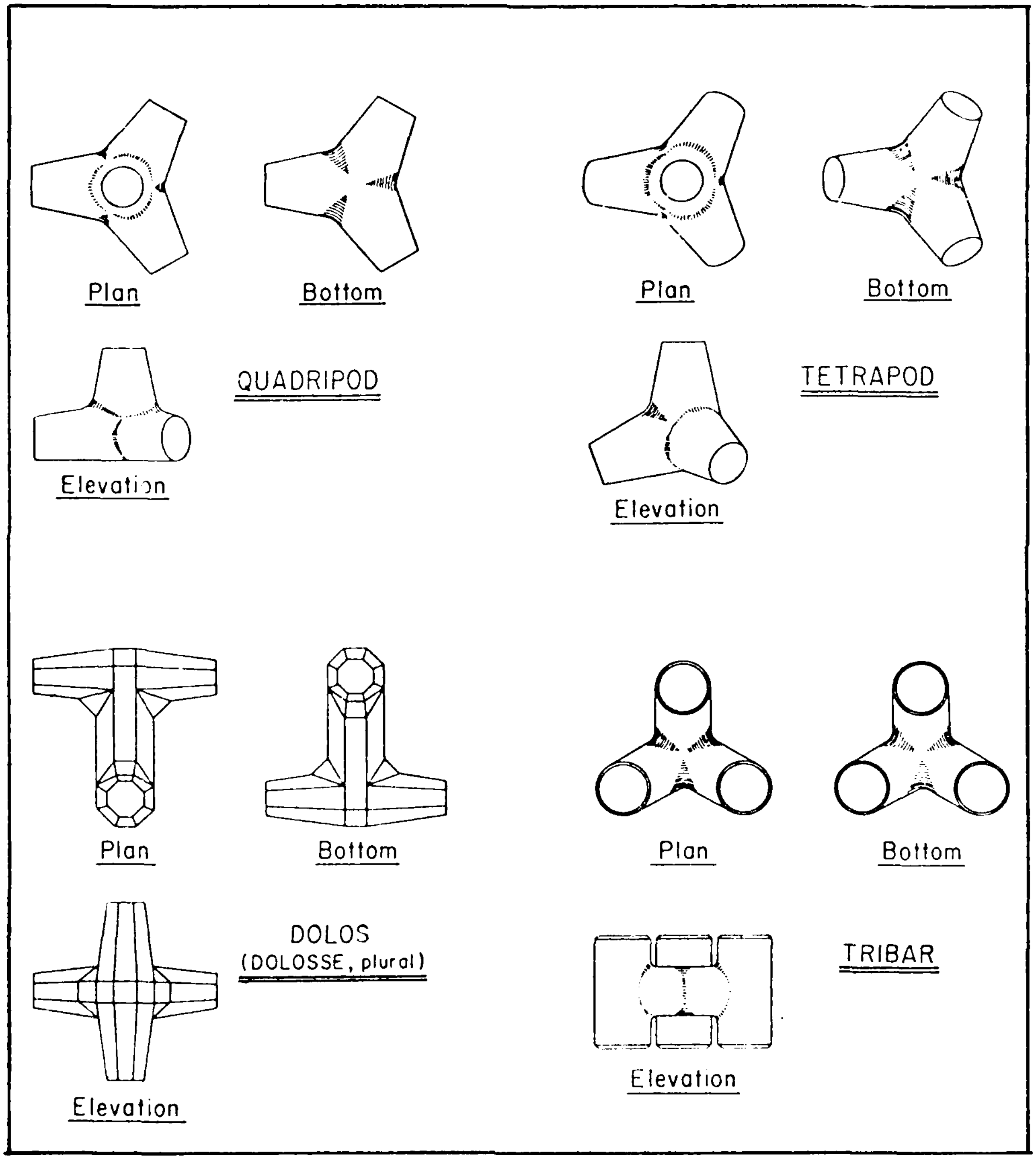


Figure 52. Concrete armor units (U.S. Army, Corps of Engineers, CERC, 1977).

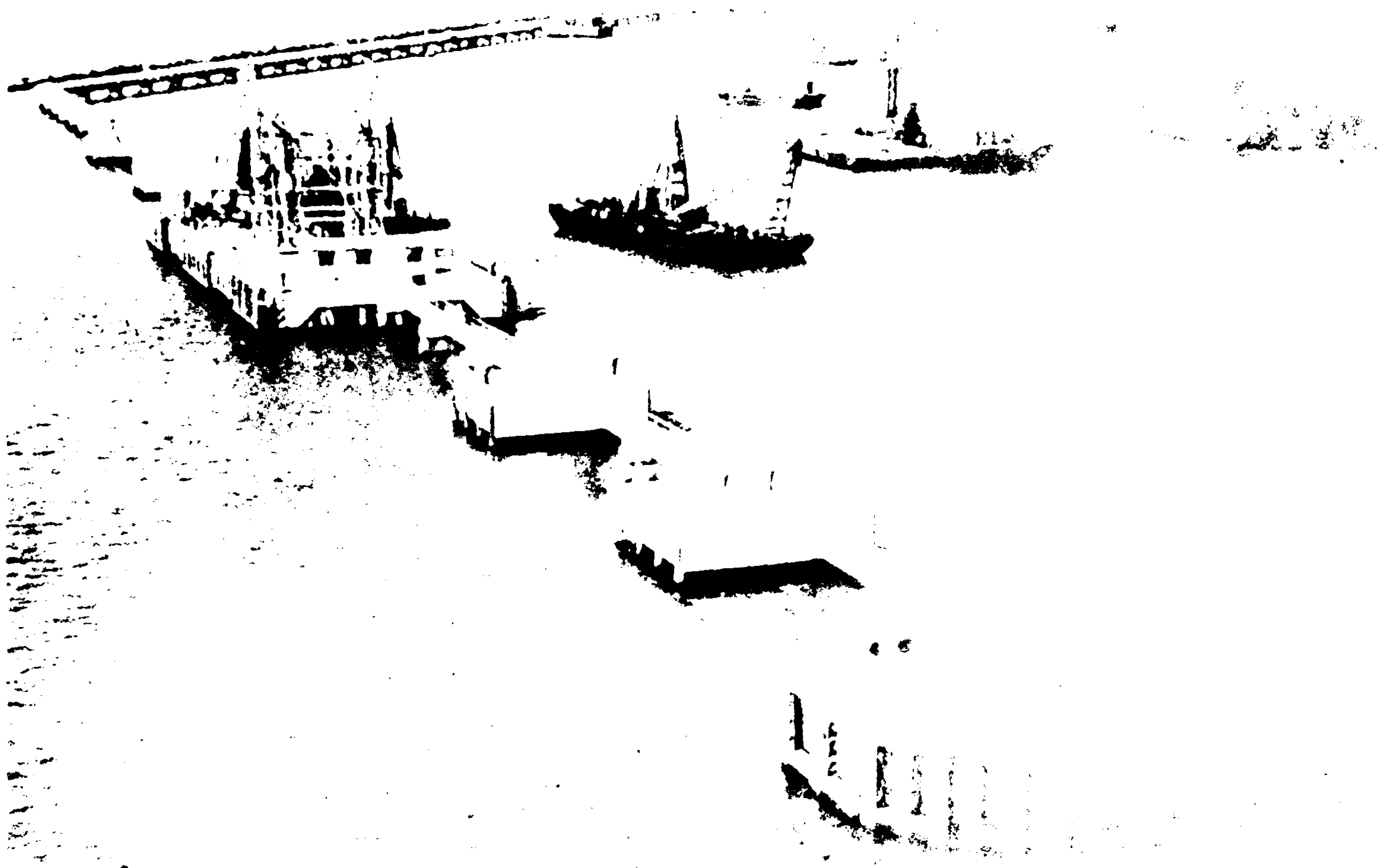


Figure 33. Pier 5, Port of Callao, Peru (photo courtesy of American Association of Port Authorities).

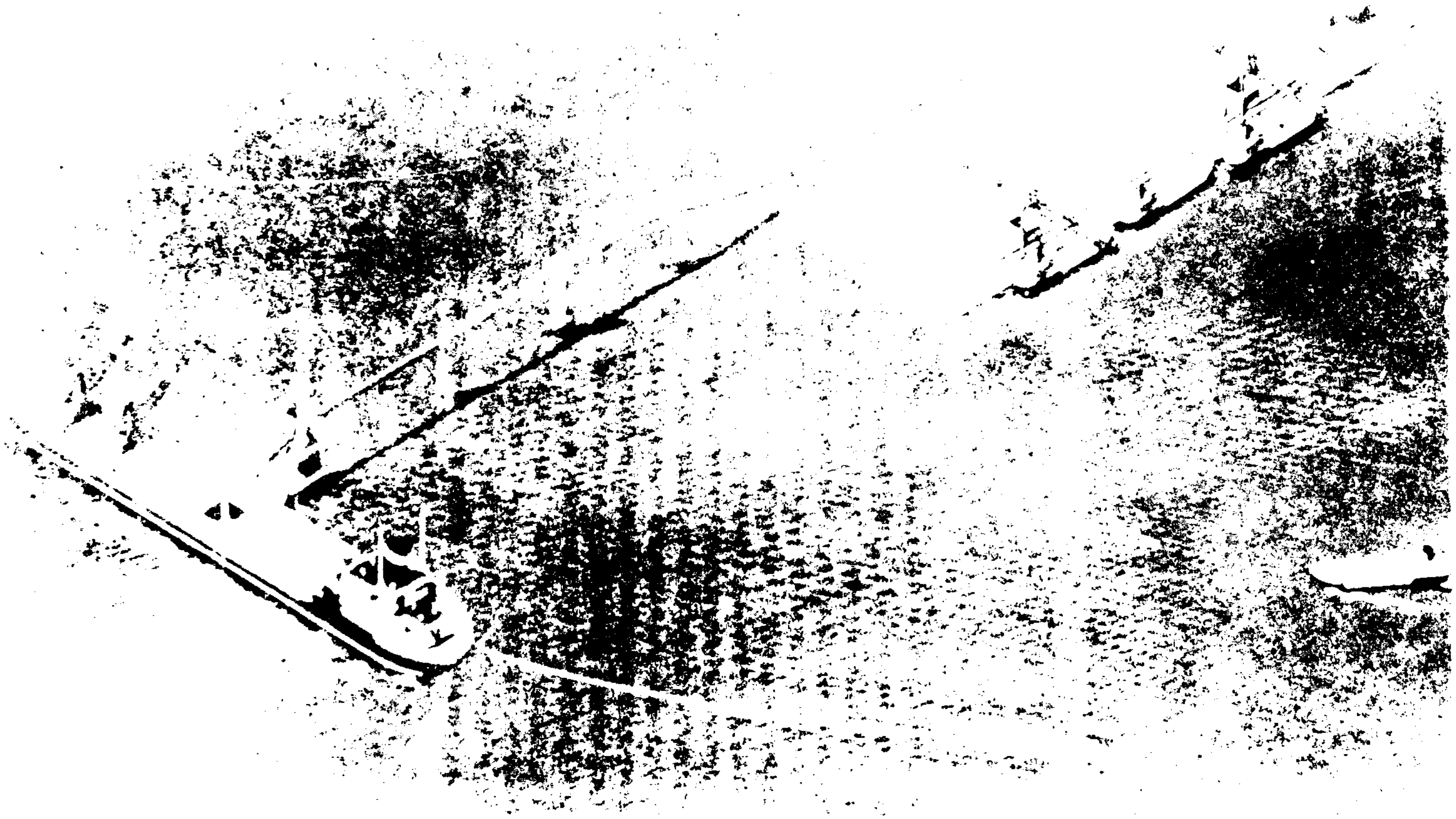


Figure 54. Artificial island on Continental Shelf off Brazil (photo courtesy of AAPA).

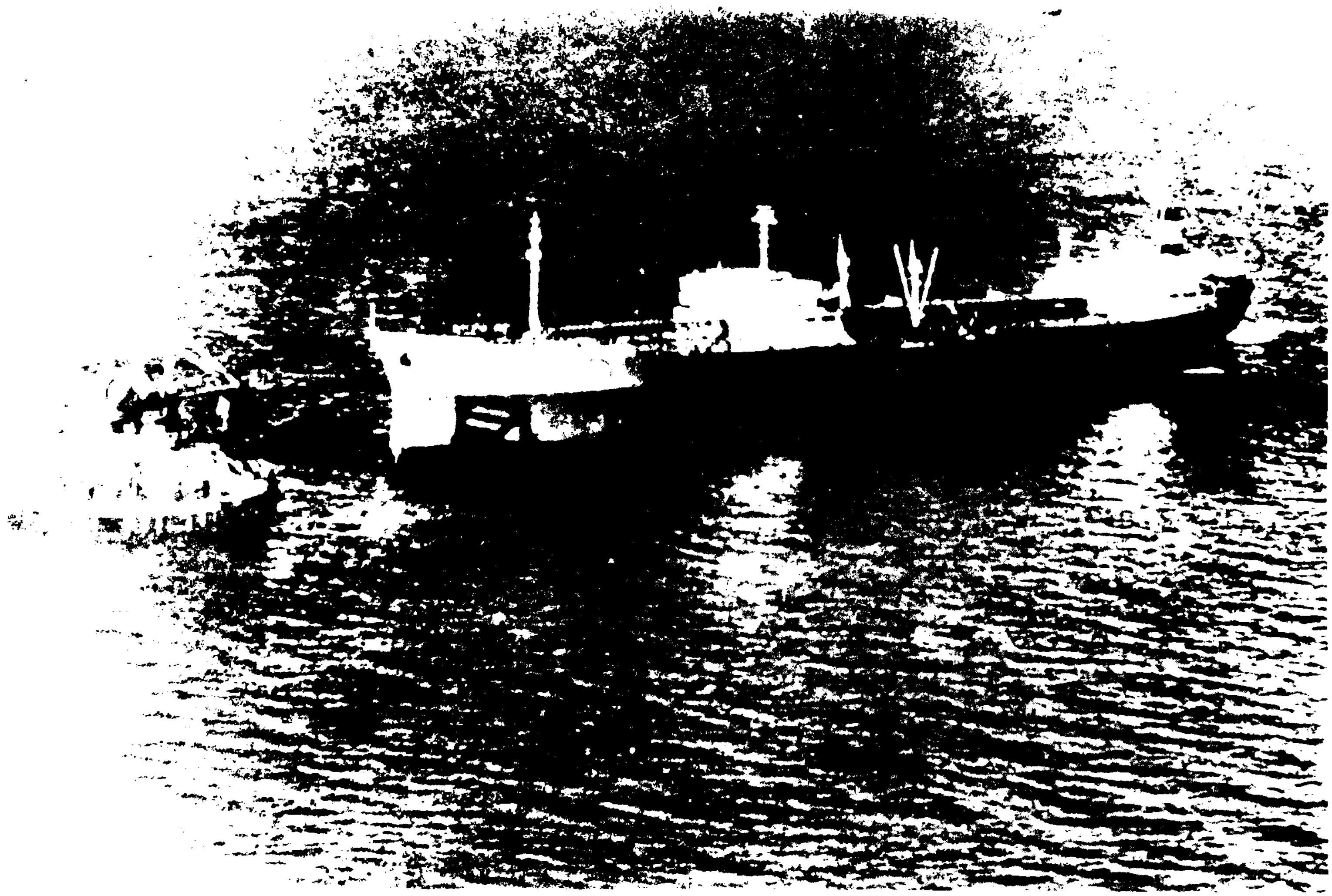


Figure 35. Fixed single point mooring at Marsa El Brega, Libya (photo courtesy of AAPA).

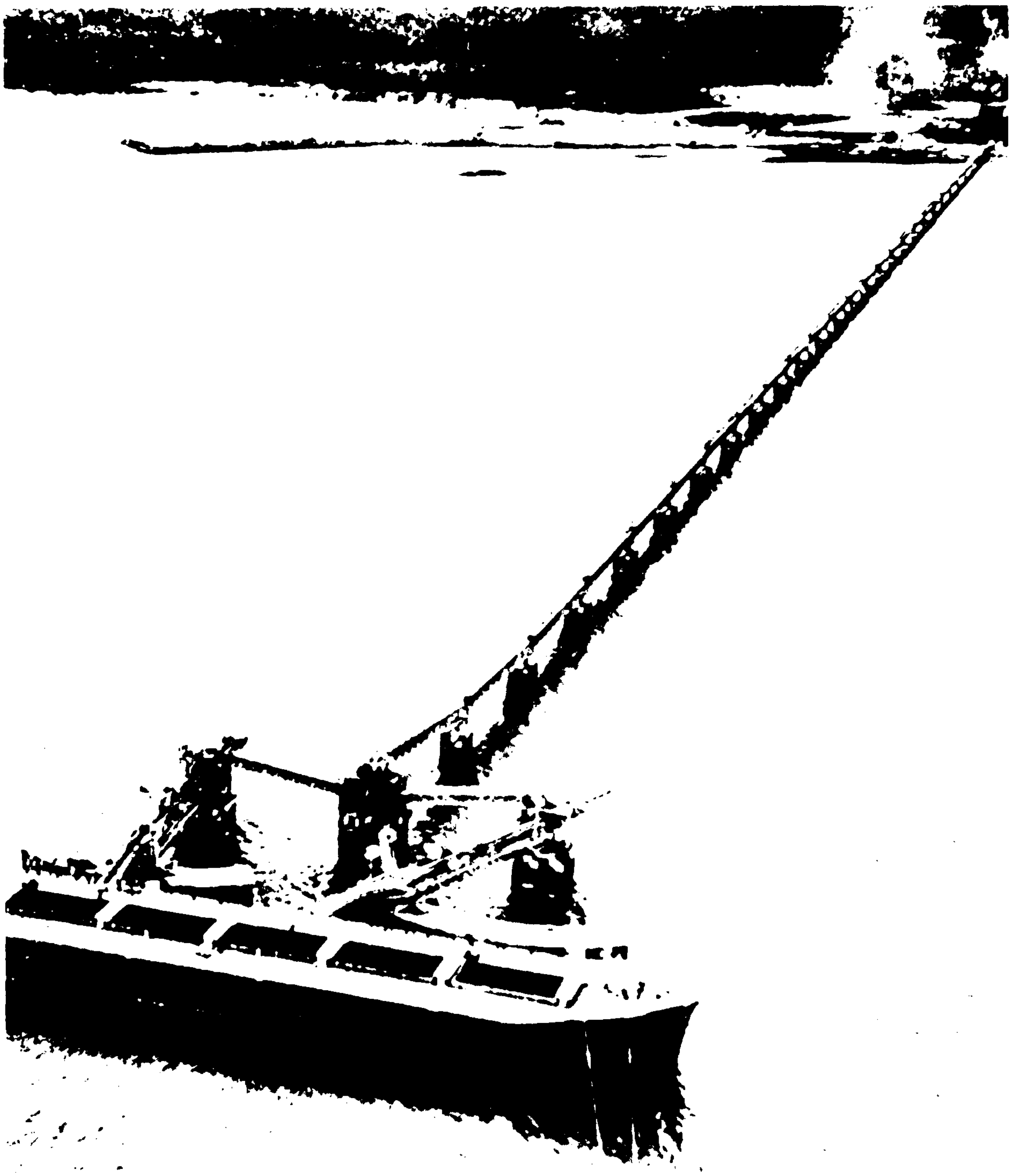


Figure 56. Port Lotta, Tasmania, ore terminal (photo courtesy of AAPA).

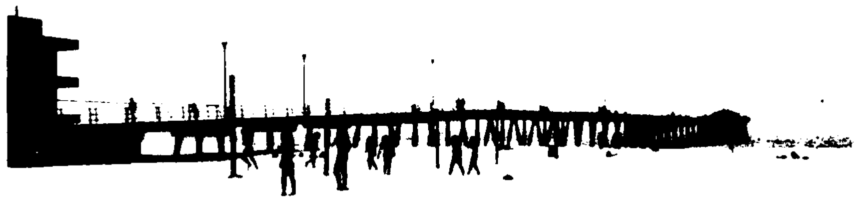


Figure 37. Hermosa Beach recreation pier.

These piles may vary in cross section from 0.15-meter (6 inch) diameter round piles to 0.76-meter (30 inch) solid square or octagonal piles and 1.2 meter (4 foot) round hollow piles. Hollow piles usually have a 0.15- to 0.30 meter wall. The restrictions on concrete pile size are determined by the equipment required to manufacture them, e.g. the pile bed, forms and, if required, prestressing equipment as well as the pile handling equipment such as cranes, barges and piledriver.

(3) Submerged Structures. Concrete is an ideal material for the construction of submerged structures. It may be used for monolithic submerged structures such as structural elements of bridges or precast-prestressed for pipelines, intake and outfall structures, and bridge piers. Other submerged structures usually built of concrete include tunnels for vehicular and railroad traffic and utilities.

(4) Floating Structures. Many concrete pontoons of various shapes and size have been constructed as parts of pontoon bridges, quays, wharves, and floating facilities for small boats and seaplanes. Floating breakwaters of precast reinforced concrete pontoons have been installed in Tenakee Springs, Sitka, and Ketchikan, Alaska, and Blaine, Everett, and Port Orchard, Washington. Other structures such as skiffs, launches, scows, barges, floating drydocks, and permanent offshore structures have been constructed of concrete. The construction of fixed breakwaters by floating precast units into place is not uncommon. Caisson units are constructed on a land site, floated into position, sometimes thousands of miles from the construction site, then submerged on the ocean bottom and filled with sand or dredge material. Most any type of floating or submersible structures, at one time or another has been built of concrete.

(5) Access and Roadway Structures. Concrete is used for roadways, bridges, structural anchors, and foundations as a part of coastal structures. Overpasses, footbridges, drainage facilities, and concrete pipe are also ancilliary to many coastal structures.

(6) Ocean Outfall and Discharge Structures. Because of the excellent durability of concrete in the coastal environment, many ocean outfall and discharge structures in the coastal zone are made of concrete. These structures accommodate rain and flood water runoff as well as industrial and domestic wastes. Ancilliary facilities, such as settling ponds and pumping plants required to make these systems work are also frequently constructed of concrete.

VI. OTHER TYPES OF CONCRETE AND GROUT

1. Bituminous Concrete.

Asphalt is a primary ingredient of all bituminous concretes. It is a natural constituent of many petroleums in which it exists in solution. If the solvent oils are removed by evaporation or distillation from crude petroleum, an asphalt residue remains. Asphalt is a cement, readily adhesive, highly waterproof, and durable. It is a plastic substance and imparts controllable flexibility to mixtures of mineral aggregates with which it is usually combined.

The three general catagories of bituminous concrete used in coastal structures are: asphalt concrete, a mixture of asphalt cement and both fine and coarse aggregate, placed and compacted to form a monolithic structure; sand asphalt, essentially a type of asphalt concrete with coarse aggregate omitted; and asphalt mastic, basically a sand asphalt having a sufficiently fluid consistency during placement to allow it to flow into voids of a rock structure such as a breakwater or jetty.

a. Types of Asphaltic Materials. The following terms relating to asphalt are taken from "Asphalt in Hydraulics" (The Asphalt Institute, 1976):

"(1) Asphalt Cement. Asphalt that is refined to meet specifications for paving, industrial, or special purposes.

(2) Asphalt Concrete, Hydraulic Type. Similar to asphalt concrete for roadway paving, except, to ensure an essentially voidless mix after compaction, higher mineral filler and asphalt contents are used.

(3) Asphalt Facing. An asphalt surface designed to resist erosion, abrasion, water pressure, and in some instances, ice pressure. A facing may, in addition, also act as an impermeable layer to prevent leakage through the structure. It may also be termed an asphalt lining or asphalt revetment (see below).

(4) Asphalt Grout. A mixture of asphalt, sand, and mineral filler which, when heated and mixed, will flow into place without mechanical manipulation. It is used to bind together a layer of coarse stone of more or less uniform size. It may also be termed asphalt mastic (see below).

(5) Asphalt Injection. A pressurized subsurface application of asphaltic material. Usually, injections are made for the purpose of filling subsurface cavities or crevices in the foundation soil, or voids beneath an existing pavement layer, primarily for controlling water seepage.

(6) Asphalt Lining. That part of a hydraulic structure that functions as a durable, erosion-resistant surface. Usually, its

most important function is as a waterproof barrier holding water or other liquid inside the structure.

(7) Asphalt Mastic. A mixture of mineral aggregate, mineral filler and asphalt in such proportions that the mix can be applied hot by pouring or by mechanical manipulation; it forms a voidless mass without being compacted.

(8) Asphalt Mattress, Slab. Terms, according to size, denoting prefabricated flexible units composed of an asphalt mastic mixture reinforced with mesh, netting, lines, or cables as required.

(9) Asphalt Membrane. A relatively thin layer of asphalt formed by spraying a high-viscosity, high softening point asphalt cement in two or more applications over the surface to be covered. It is normally about 6 millimeters (1/4 inch) thick and is used for waterproofing or sealing. It is buried to protect it from weathering and physical damage.

(10) Asphalt Mat. A felt or fabric sheet impregnated or coated with asphalt to form a watertight lining or membrane usually 6 millimeters or less in thickness. It may be a sheet that is first installed in place with the asphalt applied following installation, or it may be a finished material that is watertight and ready for installation.

(11) Asphalt Revetment. A protective asphalt facing on a sloped surface, usually placed for the purpose of protecting an embankment from erosion. Revetments may or may not extend all the way to either the toe or crest of the sloped embankment. The term subaqueous refers to that part of a revetment placed under the surface of the water. Upper bank paving is that part placed above the surface of the water.

(12) Impermeable Asphalt Mixes. Asphalt mixes having low voids, (usually less than 4 percent) after installation, designed to prevent the passage of water.

(13) Porous Asphalt Mixes. Asphalt mixes that permit the free flow of water through the mix. Porous asphalt mixes are divided into two general classifications: permeable asphalt mixes and open-graded asphalt mixes (see below).

(14) Permeable Asphalt Mixes. Asphalt mixes having medium voids after installation, designed to permit the free passage of water through the lining to and from the supporting layer or embankment.

(15) Open-Graded Asphalt Mixes. Asphalt mixes having high voids, designed to provide a free drainage layer underneath an impermeable lining.

(16) Prefabricated Asphalt Panels. A layer of a very dense mixture of asphalt and filler sandwiched between two layers of some tough, asphalt-impregnated material and usually coated with waterproofing asphalt."

b. Properties of Asphalt Materials. Asphalt has many properties that make it particularly suitable for use in hydraulic and costal zone structures. It is versatile in form and application. Asphalt can be used alone (as in an asphalt membrane), or it can be mixed with other materials producing mixes for a variety of purposes. It can be combined with graded aggregate to form a voidless and impermeable mix. On the other hand, it can be combined with an open-graded aggregate to form a porous mixture allowing free passage of water.

Asphalt is stable in the presence of nearly all chemically-laden substances. It is normally unaffected by the usual concentrations of acid, salt, and other waste solutions. This important characteristic makes it useful for waterproofing reservoirs. However, since asphalt is refined from petroleum, other petroleum-based products (which are solvents of asphalt) cannot be stored in asphalt-lined structures.

An important property of asphalt is its flexibility. This allows asphalt structures to conform to slight irregularities in the subgrade, and to adjust to small differential settlements that inevitably occur after the completion of a structure.

The physical properties of asphalt mixes generally depend on stress conditions and temperature. The ingredients that comprise asphalt mixes have completely different characteristics. The mineral aggregate that makes up the major part of the mix is mainly elastic. The asphalt part, on the other hand, behaves as a viscous liquid at high temperature and under impact load; consequently, asphalt mixtures have both plastic and elastic properties.

For many years asphalt cement has been graded on the basis of the penetration test, an empirical measures of consistency. Recently, however, the penetration grading of asphalt cements has been replaced by the more fundamental viscosity grading. Two systems of viscosity grading are currently used. The AC system is based on the viscosity of the original asphalt cement. The AR system, used mostly on the Pacific coast of the United States, is based on the viscosity of the residue of the asphalt cement after it has been subjected to hardening conditions approximating those occurring in normal hot-mix plant operations.

The relationships between the various grading systems are shown in Figure 58.

c. Asphalt Mixes.

(1) Objectives of Asphalt Mix Design. The design of asphalt mixes, as with other engineering materials designs, is largely a matter of selecting and proportioning materials to obtain the desired properties in the finished construction. The overall objective for the design of asphalt mixes is to determine an economical blend and gradation of aggregates

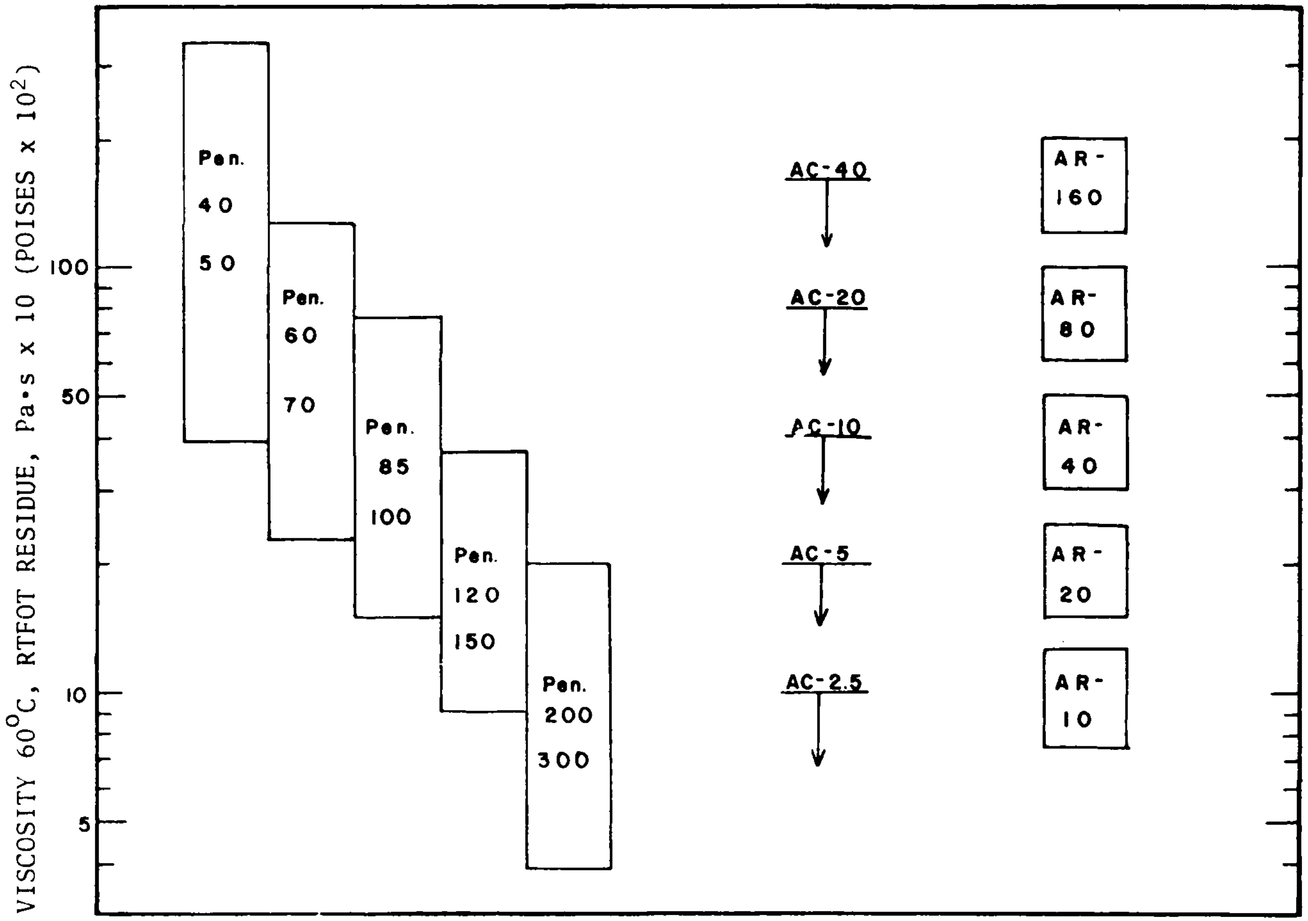


Figure 38. Comparison of penetration grade and viscosity grades of asphalt cement (based on rolling thin film oven test--RTFOT--residue for AR grades and penetration grades; thin film oven test--TFOT--residue for AC grades).

(within the limits of the project specifications) and asphalt that yields a mix having:

(a) Sufficient asphalt to ensure durability;

(b) sufficient mix stability to satisfy the demands of designed use without distortion or displacement;

(c) sufficient voids in the total compacted mix to allow for a slight amount of additional compaction under loading without flushing, bleeding, and loss of stability, yet low enough to keep out harmful air and moisture; and

(d) sufficient workability to permit efficient placement of the mix without segregation.

(2) Evaluation and Adjustment of Mix Designs. Often, in the process of developing a specific mix design, it is necessary to make several trial mixes to find one that meets the criteria of the design method used. Each trial mix design, therefore, serves as a guide for evaluating and adjusting the trials that follow. For preliminary or exploratory mix designs it is advisable to start with an aggregate of a gradation that approaches the median of the specification limits. Initial trial mixes for establishing the job-mix formula, however, must have an aggregate gradation within the specification limits that the central mixing plant is producing or is capable of producing.

Where the initial trial mixes fail to meet the design criteria it will be necessary to modify or, in some cases, redesign the mix. Adjustments in the grading of the original aggregate blend will be required to correct the deficiency.

For many engineering materials, the strength of the material frequently is thought of as denoting quality; however, this is not necessarily the case for hot-mixed asphalt paving. Extremely high stability is often obtained at the expense of lowered durability, and vice versa. Therefore, in evaluating and adjusting mix designs always keep in mind that the aggregate gradation and asphalt content in the final mix design must strike a favorable balance between the stability and durability requirements for the use intended. Moreover, the mix must be produced as a practical and economical construction operation.

Grading curves are helpful in making necessary adjustments in mix designs. For example, curves determined from the Fuller equation, a version of the maximum density equation using the power 0.5, represent maximum density and minimum voids in mineral aggregate (VMA) conditions.

The Fuller equation is:

$$p = 100(d/D)^{.5}$$

where p is the total percentage passing given sieve, d the size of sieve opening, and D the largest size (sieve opening) in gradation. Mixtures described by such curves tend to be workable and readily compacted.

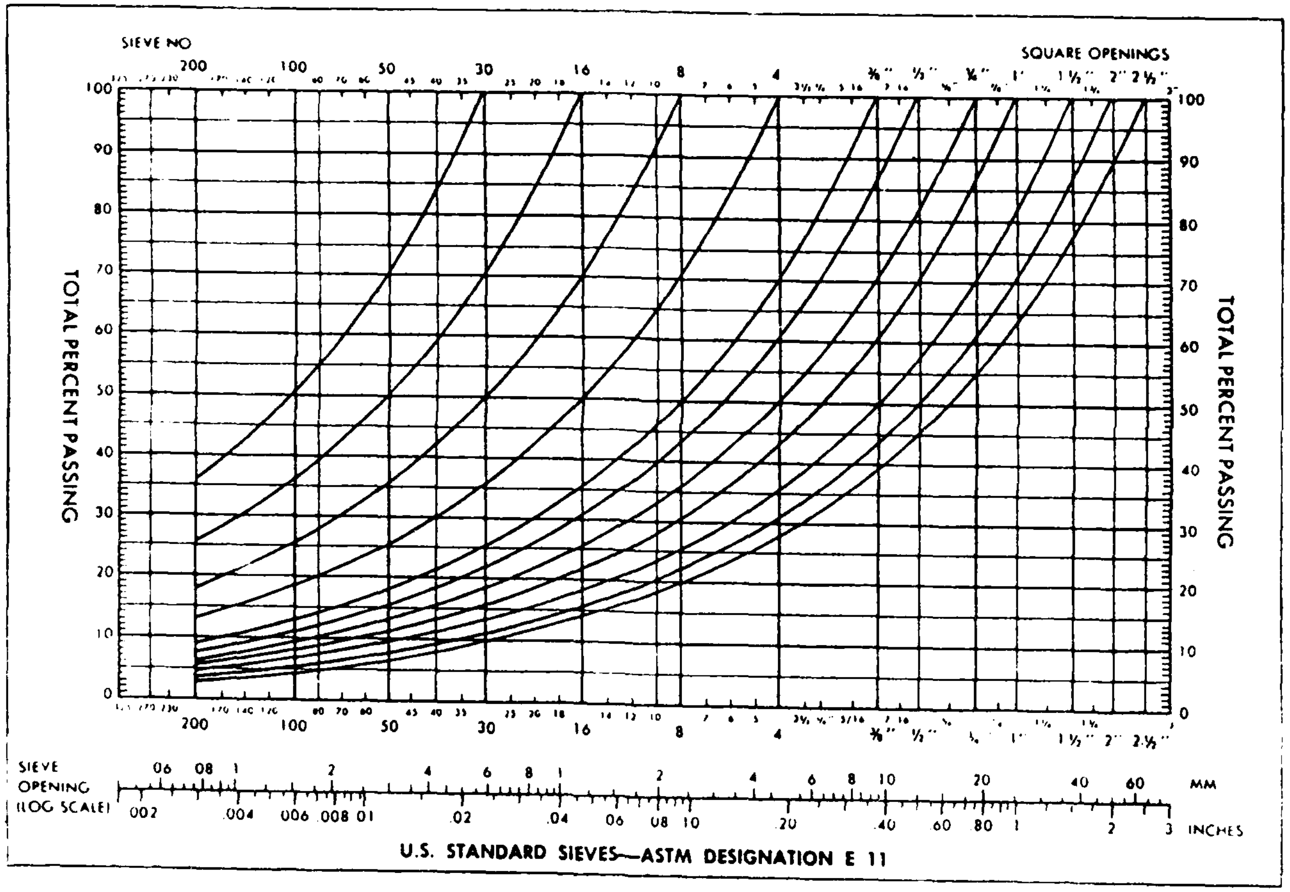


Figure 39. Fuller maximum density curves on standard semilog grading chart {American Concrete Institute (ACI), 1979}.

However, their void contents may be too low. Usually, deviations from these curves will result in lower densities and higher VMA. The extent of change in density and VMA depends on the amount of adjustment in fine or coarse aggregate. Figure 39 illustrates a series of Fuller maximum density curves plotted on a conventional semilog grading chart.

Figure 40 illustrates maximum density curves determined from the maximum density equation raised to the 0.45 power $\{p = 100(d/D)^{.45}\}$ and plotted on the Federal Highway Administration grading chart (based on a scale raising sieve openings to the 0.45 power), which many designers find convenient to use for adjusting aggregate gradings. The curves on this chart, however, need not be determined from the maximum density equation. They may be obtained by drawing a straight line from the origin at the lower left of the chart to the desired nominal maximum particle size at the top. For processed aggregate, the nominal maximum particle size is the largest sieve size listed in the applicable specification upon which any material is permitted to be retained. Gradings that closely approach this straight line usually must be adjusted away from it within acceptable limits to increase the VMA values. This allows enough asphalt to be used to obtain maximum durability without the mixture flushing.

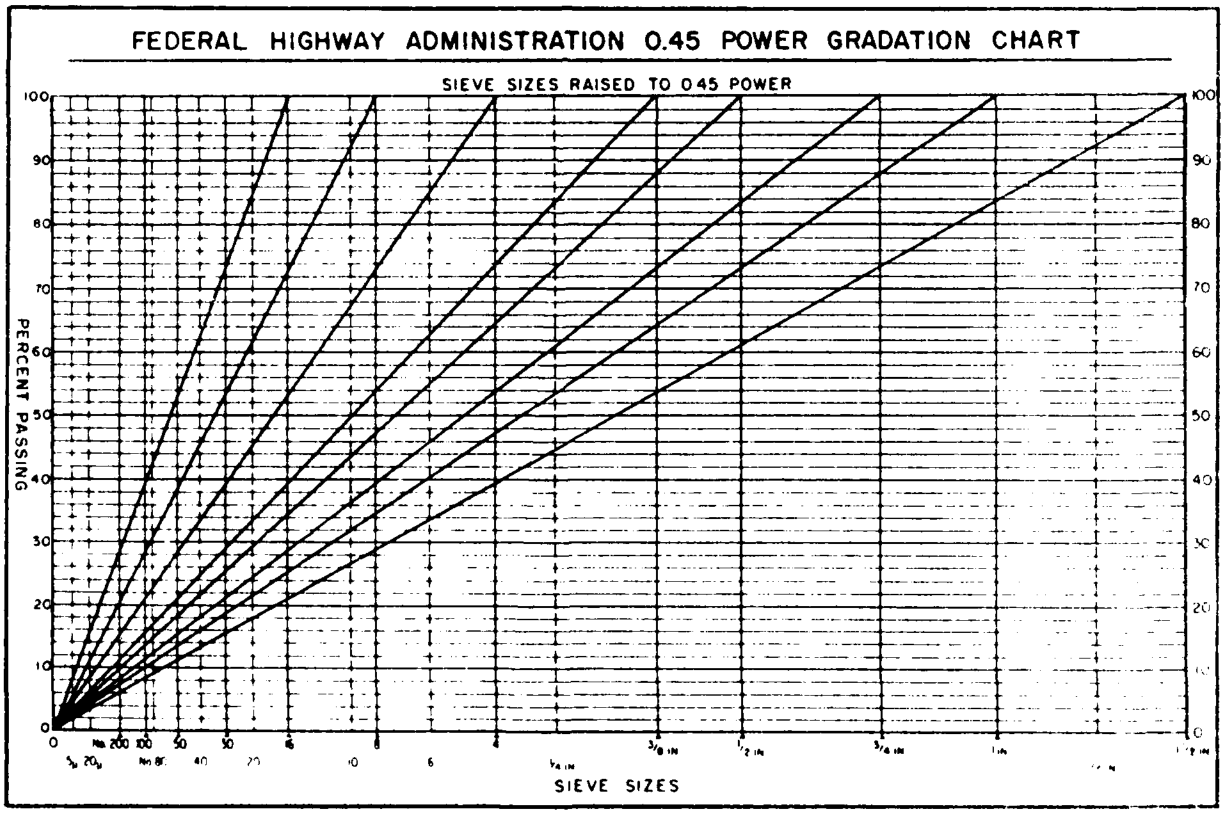


Figure 40. Maximum density curves on Federal Highway Administration 0.45 power gradation chart (Federal Highway Administration, 1975).

The following is a general guide for adjusting the trial mix, but the suggestions outlined may not necessarily apply in all cases.

(a) Voids Low, Stability Low. Voids may be increased in a number of ways. As a general approach to obtaining higher voids in the mineral aggregate (and therefore providing sufficient void space for an adequate amount of asphalt and air voids) the aggregate grading should be adjusted by adding more coarse or more fine aggregate.

If the asphalt content is higher than normal and the excess is not required to replace that absorbed by the aggregate, the asphalt content may be lowered to increase the voids. It must be remembered, however, that lowering the asphalt content increases the void content and reduces the film thickness, which decreases the durability of the pavement. Too great a reduction in film thickness also may lead to brittleness, accelerated oxidation, and increased permeability. If the above adjustments do not produce a stable mix, the aggregate may have to be changed. It usually is possible to improve the stability and increase the aggregate void content of the mix by increasing the amount of crushed materials. With some aggregates, however, the freshly fractured faces are as smooth as the waterworn faces and an appreciable increase in stability is not possible. This is generally true of quartz or similar rock types.

(b) Voids Low, Stability Satisfactory. Low void content may result in instability or flushing after the mix has been exposed to design loads for a period of time because of reorientation of particles and additional compaction. It also may result in insufficient void space for the amount of asphalt required for high durability, even though stability is satisfactory. Degradation of the aggregate under the action of use may also lead to instability and flushing if the void content of the mix is not sufficient. For these reasons, mixes low in voids should be adjusted by one of the methods given above, even though the stability appears satisfactory.

(c) Voids Satisfactory, Stability Low. Low stability when voids and aggregate grading are satisfactory may indicate some deficiencies in the aggregate. Consideration should be given to improving the quality as discussed above.

(d) Voids High, Stability Satisfactory. High voids are frequently, although not always, associated with high permeability. High permeability by permitting circulation of air and water through the asphalt cement may lead to premature hardening of the asphalt. Even though stabilities are satisfactory, adjustments should be made to reduce the voids. This usually may be accomplished by increasing the mineral dust content of the mix. In some cases, however, it may be necessary to select or combine aggregates to more closely approximate the gradation of a maximum density grading curve.

(e) Voids High, Stability Low. Two steps may be necessary when the voids are high and the stability is low. First the voids are adjusted by the methods discussed above. If this adjustment does not also improve the stability, the second step should be an improvement of aggregate quality as discussed above.

(3) Aggregate Gradations and Fractions. For the purpose of specifications and test reporting it is almost universal practice to specify the gradation of aggregates on the basis of the total aggregate gradation, i.e., total percent by weight passing the designated sieve sizes. The individual fractions of the total aggregate gradation, however, are designated as follows:

(a) Coarse aggregate (retained No. 8 sieve);

(b) fine aggregate (passing No. 8 sieve); and

(c) mineral dust (passing No. 200 sieve).

It is also important to note that the aggregate gradations as well as the individual fractions are specified independently of the total mix; i.e., the total aggregate equals 100 percent.

Aggregate materials often are identified in broader terms as: rock, sand, and filler. These terms usually are applied to the stockpiled materials supplied to the job site. The following definitions appear to have the greatest usage:

(a) Rock: material that is predominantly coarse aggregate (retained No. 8);

(b) sand: material that is predominantly fine aggregate (passing No. 8); and

(c) filler: material that is predominantly mineral dust (passing No. 200).

d. Functions in Coastal Structures.

(1) General. Asphalt has many properties that make it particularly suitable for use in hydraulic structures. It is versatile in form and application. Asphalt can be used alone (as in an asphalt membrane), or it can be mixed with other materials producing mixes for a variety of purposes. It can be combined with graded aggregate to form a voidless and impermeable mix, or it can be combined with an open-graded aggregate to form a porous mixture allowing free passage of water.

There are many types of asphaltic materials used in hydraulic applications. Each type can be classified in one of the following distinct categories:

(a) Impermeable asphalt mixes,

(b) porous asphalt mixes,

(c) asphalt mastics,

(d) asphalt cement, and

(e) prefabricated asphalt materials.

These materials can be used in various forms to waterproof, protect, or reinforce a structure. Table 25 shows how each type of asphalt material may be used to perform these various functions.

(2) Impermeable Asphalt Concrete Linings. Impermeable asphalt mixes are similar to asphalt mixes for highway paving except that, since a low void content mix is required to ensure impermeability, they usually have higher mineral filler and asphalt-cement contents. Also a harder, or more viscous, grade of asphalt cement normally is used. Mixes are prepared in an asphalt mixing plant and placed with conventional, or as shown in Figure 41, special paving equipment. Compaction during paving is necessary to produce the required impermeability.

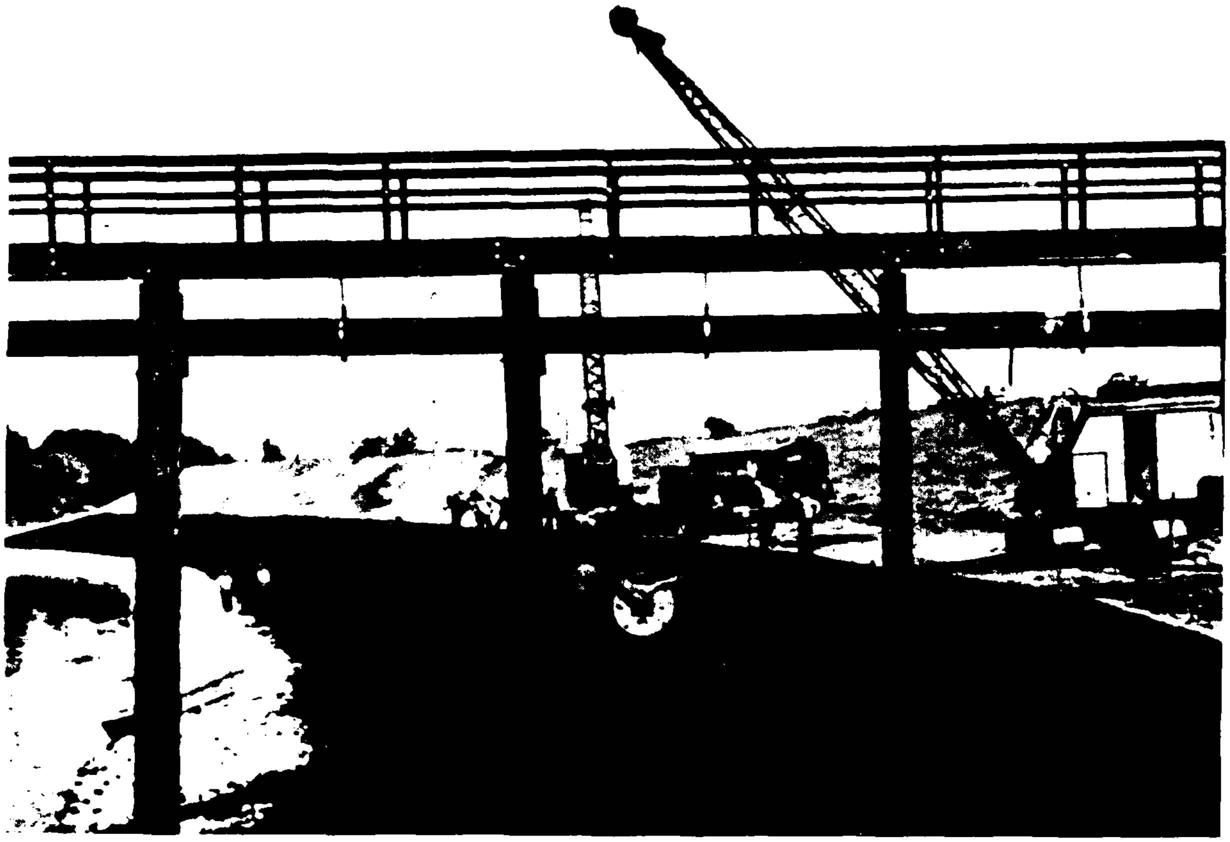


Figure 41. Roller operated by a dragline compacts the asphalt revetment, San Joaquin River, California (photo courtesy of ACI).

The primary purpose of impermeable asphalt mixes is to waterproof hydraulic structures. Watertight linings are used to impound water in reservoirs, ponds, and lagoons; to waterproof dams, dikes, and embankments; and to prevent seepage losses in canals and channels. They are most often used as surface linings, since they are resistant to wave action and the erosive effects of water currents.

Revetments constructed with impermeable asphalt mixes are used for bank protection on streams, reservoirs, lakes, and shorelines. Waterproofing

Table 25. Applications of asphaltic materials for hydraulic structures.

Material	Function		
	Waterproof	Protect	Reinforce
Impermeable Asphalt Mixes	Surface or exposed linings	Surface or exposed linings	
Porous Asphalt Mixes		Permeable surface linings, Open-graded subsurface drainage layers	
Asphalt Mastics	Surface linings, Seal coats, Cutoff walls, Dam cores, Subsurface injection	Surface linings, Seal coats	Grouting, Penetration treatments
Asphalt Cement	Membranes, Seal Coats Subsurface pressure injections		Grouting, Penetration treatments
Prefabricated Asphalt Materials	Panels, Sheets, Mattresses, Slabs	Panels, Mattresses, Slabs	

properties are not necessarily required in these instances, but quality asphalt concrete linings having low voids effectively resist the destructive effects of wave and current action as well as their abrasive effects (Figs. 42 and 43). Impermeable asphalt mixes may be used for the entire lining of the structure. They may also constitute a part of a more complex lining. They can, for example, be placed as the surface of a composite section made up of different asphalt layers.

(3) Porous Hot-Mix Asphalt Linings. Porous asphalt mixes for hydraulic structures are characterized by the absence or reduced amount of fine aggregate or sand in the mix. As a consequence, the asphalt content is also reduced. The mixes have interconnected pores that permit passage of water. A harder, or more viscous, grade of asphalt cement is desirable in these mixes to allow sufficient film thickness and to prevent drainage from the aggregate. This choice of asphalt also provides additional cohesion in the mix between the aggregate particles.

There are two types of porous asphalt linings: permeable and open-graded. Permeable hot-mix asphalt linings serve as a cover over an earth embankment to protect it from erosion by wave action or surface runoff. Open-graded asphalt linings, with higher void content than the permeable lining, serve as drainage layers under an impermeable lining while at the same time contributing to the structural strength of the lining. In either case, the purpose is to provide free drainage to prevent hydrostatic pressures from building up in the embankment or within the lining itself. Asphalt, as a surface lining, allows water to flow to and from the embankment through the lining. As a drainage layer, asphalt collects the subsurface water, channeling it to drains for removal.

(4) Asphalt Mastic Mixes. Asphalt mastic mixes for hydraulic structures are essentially mixtures of mineral aggregate and filler where the voids in the mineral matrix are overfilled with asphalt cement. The result is an asphalt mix that can be applied by pouring or by hand-floating into place. Asphalt mixes require little or no compaction after placing because void spaces in the aggregate matrix are filled or slightly overfilled with asphalt. Asphalt mastics may be made from a variety of aggregate materials ranging from well-graded coarse and fine aggregates and mineral filler to essentially mineral filler alone with or without an additive such as asbestos fibers. The mastic is voidless except for air bubbles that may be trapped during the manufacture and placing.

Asphalt mastics can be used in several ways to waterproof, protect, or reinforce a hydraulic structure. For waterproofing, asphalt mastics have been used for cutoff walls for dams as well as for the central core of the dam itself. They are also used as exposed watertight surface linings.

Asphalt mastic mixes are erosion-resistant; therefore, they can be exposed to waves and abrasive water action. They are also used to form protective covers on embankments or over the floor of channels or estuaries that are subject to erosion. Hot mastic mixes can be placed underwater through tremies, chutes, or by simply dumping in masses. They are also used for constructing flexible slabs or mattresses that are lifted into place to form a protective blanket or cover.

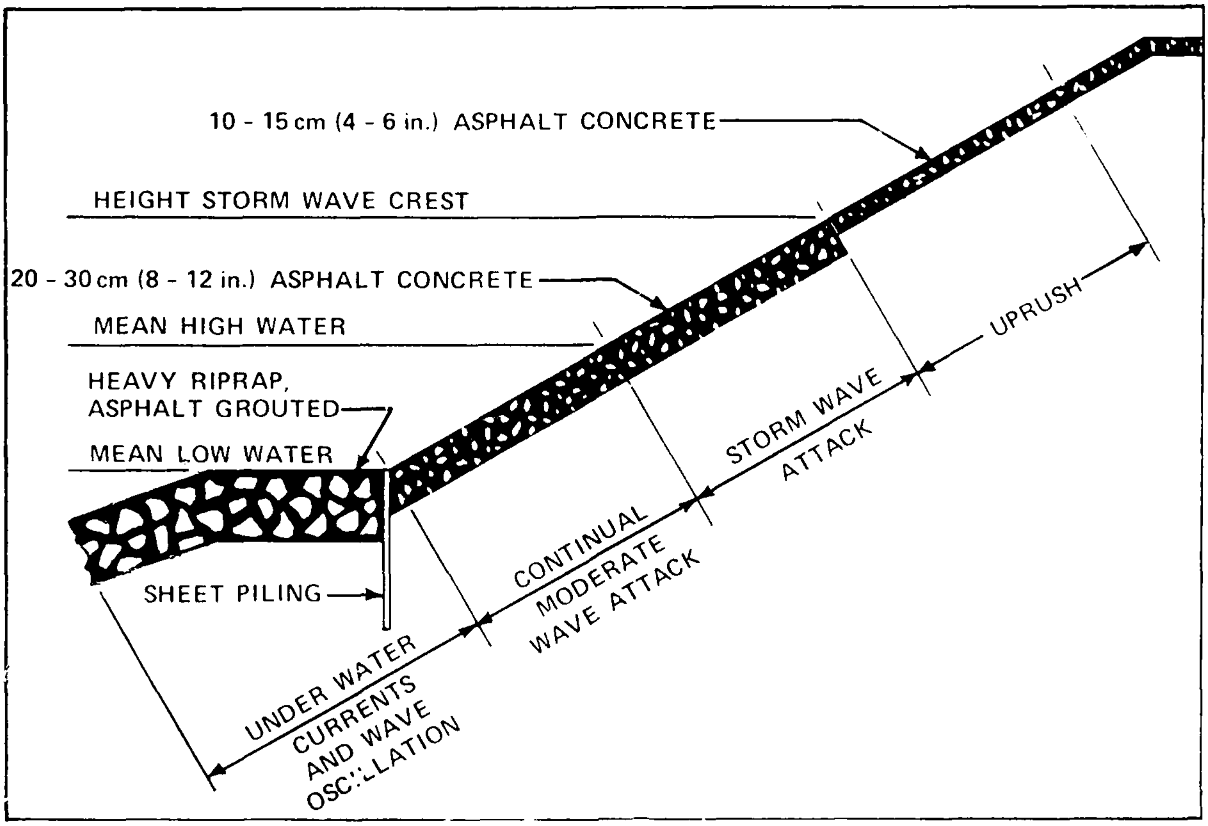


Figure 42. Seawall slope revetment.

Figure 43. Placing mix by spreader box.

For reinforcing, asphalt mastics are used as grouts to fill and plug the voids in stone structures such as jetties and revetments (Figs. 44 and 45). The binding action of the mastic tends to make one firm mass, yet mastics are flexible enough to conform to some differential settlement in the structure. Asphalt mastics are also used as joint fillers to bind stone blocks together on coastal structures, particularly in European construction.

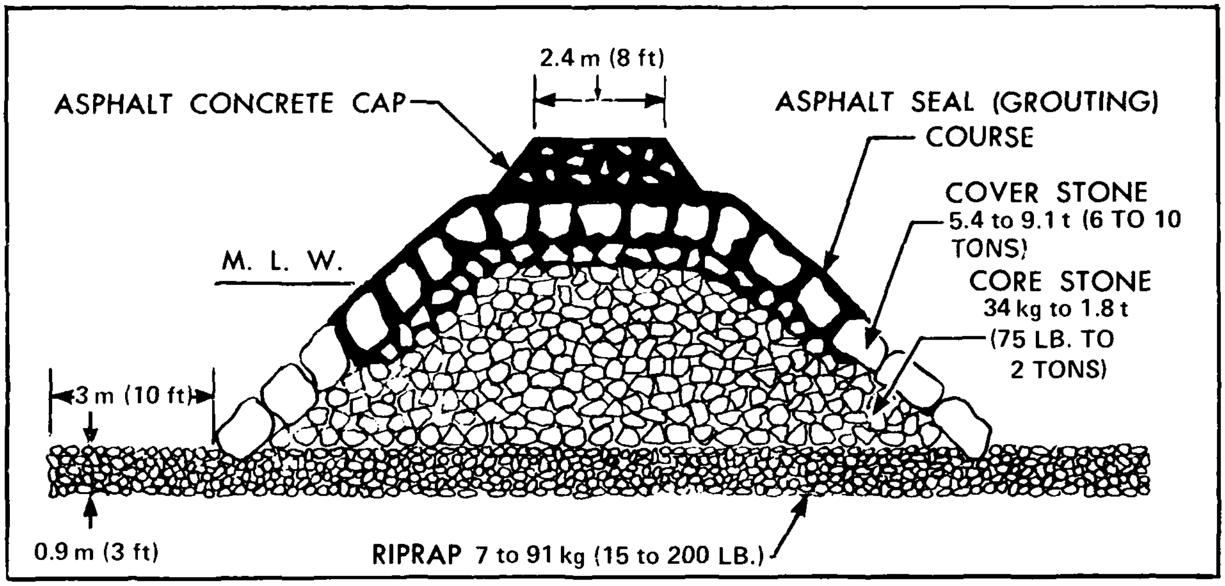


Figure 44. Cross section, south jetty, Galveston, Texas.

(5) Surface Treatments.

(a) Purposes. A surface treatment may be applied to an asphalt surface for a number of reasons. It may be designed to make the surface more watertight, or to protect it from abrasion by waves, water currents, or even by ice. A layer of mud deposited on an asphalt surface or algae and other sediments, and allowed to dry, will shrink as they dry will set up suprisingly large tensile stresses at the surface resulting in the surface curling or cracking. A surface treatment may also be used to protect the surface from mud curl or the curling of drying algae along the waterline, to give the surface a lighter color in order to reduce temperature extremes, or to reduce the rate of oxidation of the exposed asphalt surface.

(b) Sprayed Asphalt Seals. Asphalt cement or emulsified asphalt sprayed over the surface of an asphalt lining at the rate of 1 liter per square meter (0.25 gallon per square yard) will provide a film coating as much as 1 millimeter (0.04 inch) thick. A continuous film coating will fill and seal any exposed pores and increase the watertightness of the asphalt lining. It will also tend to fill and seal small cracks in the surface that may have been caused by improper rolling procedures in compacting the lining. The surface should be clean, dry, and free from

Figure 45. Galveston jetty with asphalt seal (photo courtesy of Asphalt Institute).

loose material. Its temperature should preferable exceed 38° Celsius (100° Fahrenheit). A sloped surface usually necessitates hand spraying. This should be done in a back-and-forth sweeping motion to build up the film and to keep the asphalt from flowing down the slope.

(c) Asphalt Mastic Seals. In addition to providing a seal, asphalt mastics applied to the surface of asphalt linings provide protection from mechanical abuse. Asphalt mastics, generally placed on an asphalt lining with a screed, permit a heavier coating than sprayed applications, and well-designed mixtures can make the surface resistant to abrasion by waves, or scouring by waterborne sands. Asphalt mastic mixtures for this purpose are essentially blends of mineral filler and asphalt cement.

(d) Prefabricated Asphalt Panels. The typical prefabricated asphalt panel consists of a core of ductile, blown or oxidized asphalt (asphalt which has certain natural characteristics changed by blowing air through it at elevated temperature) fortified with mineral fillers and reinforcing fibers. The ingredients are blended and molded under heat and pressure. The core is then sandwiched between protective sheets and a protective coating of hot-applied asphalt cement. The protective sheets may be an asphalt-impregnated felt, or plasticized or flexible glass fabrics (Fig. 46).

Figure 46. Lining ditch with prefabricated asphalt panels.

Asphalt panels are usually about 13 millimeters (1/2 inch) thick, but they are available as thin as 3 millimeters (1/8 inch) thick. They are usually 1.0 to 1.2 meters (3 or 4 feet) wide and 3 to 6 meters (10 to 20 feet) long for handling and placing.

The most extensive use of prefabricated asphalt panels has been in lining and waterproofing all types of water storage reservoirs, including domestic water reservoirs, sewage lagoons, industrial waste-treatment reservoirs, evaporation ponds, and reflecting pools. They are also used for lining canals and ditches, and for bank protection. Prefabricated asphalt panels have been used underneath riprap or rock reveted embankments to prevent leaching of sand and earth through the rock revetment usually caused by action of waves and tides. The development of geotechnical fabrics has largely replaced the use of asphalt panels in recent years. Asphalt panels have the advantage of providing a relatively thin watertight barrier that can be used as a surface lining. In addition, they do not require heavy machinery to install. They are useful for relining reservoirs where the concrete lining has cracked badly and where leaking has been excessive. Prefabricated asphalt panel linings are also used as an element of composite lining structures, most frequently serving as the watertight surface of a built-up lining.

(6) Miscellaneous.

(a) Sand Asphalt. Sand asphalt is a mixture of sand, with or without added mineral filler, and asphalt cement. Mineral filler added to the mix permits a higher asphalt content and makes it possible to obtain a denser, tougher, and more stable mix.

Sand asphalt has been used alone for linings, as base courses for other linings, for revetments, and for groins, although not in the coastal zone. The largest use of sand asphalt for hydraulics purposes in the United States probably has been for bank paving along the Mississippi River by the U.S. Army Corps of Engineers. The Netherlands has made extensive use of sand asphalt in the construction of seawall revetments. Typically, the base thicknesses range up to 0.20 meter (8 inches) and are usually capped with a layer of asphalt concrete.

Local sand deposits generally can be used, as gradation is not particularly critical. The asphalt cement should be AC-20 (or equivalent AR- or penetration grade) or a higher viscosity grade. A typical mix would have an asphalt content of about 6 percent. If about 5 percent mineral filler is added, the asphalt content would probably be around 8 percent. Sand asphalt mixes for linings are not as watertight as specially designed hydraulic asphalt concrete.

(b) Asphalt Prime Treatments. Priming the soil surface of a hydraulic structure with asphalt is often done to seal it temporarily or to reduce seepage until such time as waterborne sediments in the impounded water settle and plug the soil pores. Asphalt primers have also been applied to sloped embankments before placing a sprayed-asphalt membrane. The purpose, in this case, is to anchor the membrane to the slope. Primes have also been used for much the same purpose as prime treatments of roadway surfaces prior to paving operations, that is, to plug up voids and to provide a more stable surface on which to place asphalt construction. Prime treatments are neither watertight nor permanent. They are most applicable to silty sand soils that are quite permeable.

(c) Asphalt Injection. Asphalt injection is the subsurface application of asphalt pumped under pressure through pipes. The method is used to reduce leakage of a hydraulic structure through underground cracks, fissures, and cavities. Injection of asphalt into the subsurface has been done to prevent leaching of soils through rock reveted embankments at commercially developed sites to prevent surface subsidence behind the embankment.

The hot, fluid asphalt is usually pumped through heated perforated pipes dropped into drilled holes at the leakage strata levels. Once in the leakage channel, the asphalt spreads out and hardens into a tight plug or water stop. With sufficient pumping pressure, the asphalt will do this even in fissures filled with water. These asphalt plugs can adapt to slight movements in the formation and changes in water pressure.

(d) Asphalt Mattresses. Asphalt mattresses are precast sections or blankets of asphalt mastic reinforced with wire mesh and steel cables or fiber netting and lines. Generally they vary in thickness from 25 to 50 millimeters (1 to 2 inches). Their length and width are limited only by the size of the molding platform and the cababilities of the equipment used to manipulate and place them.

The reinforced asphalt mattress was developed by the U.S. Army Corps of Engineers in 1932-34 for use on underwater revetments on the banks of the lower Mississippi River. Continuous asphalt mattresses were cast on a special barge pulled into the water. Mattresses have since been adapted for use in European hydraulic structures and in Japan. Their principal function is to protect the surface on which they rest from erosion or scour by waves and currents. They are often used at the toe of a revetment or lining. After a short period, the edge of the mattress settles into the scour zone, thus stabilizing the erosive process. Asphalt mattresses are also used as linings and as protective blankets for hydraulic structures.

2. Preplaced Aggregate Concrete.

Preplaced aggregate (PA) concrete derives its name from the unique placement method by which it is made. Intrusion and grouted concretes are other common names used for this type of concrete. In this method of construction, forms are first filled with clean, well-graded coarse aggregate. Structural quality grout is then injected into the voids of the aggregate mass to produce concrete.

This method of placing concrete is especially adaptable to underwater construction, to concrete and masonry repairs, and, in general to new structures, where placement by conventional means is unusually difficult or where concrete of low volume change is required (U.S. Bureau of Reclamation, 1963). This method of placing concrete has been used in the construction of bridge piers, atomic reactor shielding, plugs for outlet works in dams and tunnels, in mine workings, and for embedment of penstocks and turbine scroll cases, as well as a great variety of repair work. Recently this process has been used for exposed aggregate and other architectural treatments. Inasmuch as preplaced aggregate concrete construction is a relatively specialized type, it is essential that the work be undertaken by well-qualified personnel experienced in this method of concrete construction.

Preplaced aggregate concrete differs from conventional concrete in that it contains a higher percentage of coarse aggregate in the finished product. Because of point-to-point contact of the coarse aggregate, as placed, drying shrinkage is about one-half the magnitude of that which normally occurs in conventional concrete {U.S. Army Engineer Waterways Experiment Station (WES), 1954, Shideler and Litvin, 1964}.

The higher percentage of coarse aggregate in the concrete has an influence on the modulus of elasticity which is slightly higher than that of conventional concrete. The other physical properties also appear to be more affected by the properties of the coarse aggregate than occurs with conventional concrete. In summary, the physical properties of preplaced aggregate concrete are similar to those of conventional concrete except that overall drying shrinkage of the former is considerably less. Accordingly, with a properly proportioned and tested grout mix and with good construction practices, allowable working stresses used for conventional concrete structural design may be used (U.S. Army Engineer, WES, 1954).

The economics of its use are a function of site conditions and job requirements. Structural forms for the concrete are usually more expensive than that required for conventionally placed concrete because greater care is needed to prevent grout leaks and placements usually require additional lateral support. However, in underwater construction, higher placing rates have been achieved by this method than by conventional placing methods.

a. <u>Types of Grouts</u>. Slurries of Portland cement and water, with or without sand, have long been used in the construction industry for filling of rock fissures. Unless sufficient pressure is applied to squeeze out excess water, settlement of solids may result in incomplete filling of voids. Clean sand-cement or soil-cement slurries may be used for low-pressure backfill grouting of rubble or rockfill where strength is not an important consideration.

As concrete technology has changed, basic grouts composed of Portland cement, sand and water have been modified to more effectively produce structural preplaced aggregate concrete. Such grouts may be modified chemically by the inclusion of admixtures such as pozzolans, fluidifiers, expansion agents, air-entraining agents, and coloring additives; or the grout may be modified mechanically by use of specially designed high-speed mixers.

b. <u>Grout and Aggregate Materials</u>.

(1) <u>Cement</u>. Grout can be made with any one of the types of cement that complies with ASTM, Standard C150, Corps of Engineers specification CRD-C 201, which would be suitable for use in conventional concrete and produce the required conditions for preplaced aggregate concrete. The type of cement should be selected in accordance with controlling factors, job conditions, and service exposures which would influence the same selection for conventional concrete.

(2) <u>Coarse Aggregate</u>. Coarse aggregate must be clean, free of surface dust and fines, sound, durable, and should conform to ASTM Standard C33, Corps of Engineers specification CRD-C133, for aggregate acceptance,

except as to grading. Importantly, the coarse aggregate should not be susceptible to excessive breakage and attrition during handling and placing in the forms. The void content of the coarse aggregate after placement in the form will customarily range between 38 to 48 percent. For economy, it is desirable to keep the void content as low as possible to minimize the required volume of the intruded grout. A low void content not only results in a saving in cementing materials, but, concomitantly, less volume change.

The maximum size aggregate depends on availability, type of construction involved, and usual limitations established for thickness of section and spacing of reinforcement bars (King, 1959). The minimum recommended size is dependent, essentially, on sand grading. Typical aggregate gradations are shown in Table 26. When grout is prepared with sand graded for use in conventional concrete, minimum coarse aggregate size should be 38 millimeters (1.5 inches). When a mason or plaster sand grading is used, minimum coarse aggregate size may be reduced to as low as 13 millimeters (0.5 inches). No limit is placed on maximum size of the coarse aggregate.

Table 26. Typical aggregate gradations for preplaced aggregate concrete prepared with fine sand grout containing pozzolan and fluidifier

Typical fine aggregate grading
Cumulative percentage passing given sieve

No. 8 (2.36 mm)	No. 16 (1.18 mm)	No. 30 (600 µm)	No. 50 (300 µm)	No. 100 (150 µm)	Pan	FM
100	97	67	31	10	0	1.95
100	98	72	34	11	0	1.85
100	96	56	36	20	0	1.92

Typical coarse aggregate grading
Cumulative percentage passing given sieve

6 in. (150 mm)	4½ in. (114 mm)	3 in. (75 mm)	1-3/4 in. (45 mm)	1-1/2 in. (38.1 mm)	7/8 in. (22.4 mm)	3/4 in. (19.0 mm)	5/8 in. (16.0 mm)	½ in. (12.5 mm)
			100	97	45	9	2	1
		100		62		4	2	1
	100	78		40		10	2	1
100		67		40		6	2	1

The coarse aggregate should be well graded up to and including the largest size which can be placed economically in the forms without excessive segregation. Gap grading, using a ratio of minimum nominal size coarse aggregate to the maximum nominal size fine aggregate of 10:1 without intermediate sizes, has been occasionally used to achieve exceptionally low void

cements. However, this grading is uneconomical for most work. Coarse aggregates as large as the largest stones capable of being carried by a man have been used with good results.

(3) Fine Aggregate. Either crushed or natural sand may be used. However, well-rounded sand grains from a natural source are preferable because such sands require less water to achieve acceptable grout fluidity. The sand should be hard, dense, durable, uncoated rock particles, and of a uniform, stable moisture content. It should conform to current ASTM Standard C33, except with respect to grading.

(4) Pozzolan. Pozzolan is used to reduce bleeding, to improve fluid properties of the mixture, and to reduce segregation of solid particles. The pozzolan combines with lime liberated during hydration of the cement to form strength producing compounds at later ages. The rate at which pozzolan contributes the heat of hydration is much slower than that of Portland cement. Both natural and manufactured pozzolans have been used, but the pozzolan most generally used and preferred is fly ash conforming to ASTM Standard C618, Corps of Engineers Specification CRD C255. Some pozzolans have caused excessive abrasion of pumping equipment and increased water requirements, so preliminary tests should be made with the selected pozzolan.

(5) Grout Admixtures. A water-reducing, set-retarding agent, known as a grout fluidifier, is commonly incorporated in the grout mixture to make it more fluid, to reduce the amount of water otherwise required for a given fluidity, to delay setting time for ease in handling with pumping equipment and to promote better penetration of the voids in the coarse aggregate. This agent is customarily a preblended material obtained commercially. It normally consists of a water-reducing agent, a suspending agent, aluminum powder, and a chemical buffer to assure properly timed reaction of the aluminum powder with alkalies in the cement. Reaction of the aluminum powder with alkalies during hydration of the cement generates hydrogen gas which causes expansion of the grout while it is fluid and provides small air bubbles within the grout. Normal dosage of the water-reducing agent in commercially available grout fluidifiers ranges from 0.20 to 0.30 percent by weight of cement plus pozzolan. Aluminum powder is normally employed in the range of 0.01 to 0.02 percent by weight of cement plus pozzolan. The fluidifier should be so proportioned that most of the expansion occurs within 3 hours after initial mixing. Preblended grout fluidifiers should conform to Corps of Engineers Specification CRD C619.

c. Grout Mix Proportioning. Grout material proportions, as in conventional concrete practice, are influenced by structural design requirements. Additionally, the grout must be so designed as to flow freely through the voids of the preplaced aggregate without appreciable segregation or water gain so that honeycombing is avoided and an intimate bond between grout and coarse aggregate particles is ensured. The importance of selecting maximum sand size, compatible with void size as determined by coarse aggregate grading, is reflected in Table 26.

Cement-to-sand ratios employed are commonly in the range of 1:1 to 1:2; although ratios as lean as 1:3 cement to sand have been used. Compressive strength and pumpability requirements limit the amount of sand which can be used in any grout (U.S. Army Engineer, WES, 1954). The grout must be

sufficiently fluid so that it will penetrate and fill all the voids in the aggregate mass, yet be of such consistency that the suspended sand and cementing materials do not settle out. For normal structural work, the ratio of cementitious materials (cement plus pozzolan) to sand should be approximately 1:1. Usually, the proportions of cement to pozzolan are 2:1, although ratios as low as 1:1 and up to 9:1 have been used on various jobs. Occasionally, the pozzolan may be omitted entirely. For a structural grout, it is usually not desirable to exceed a cement to sand ratio of 1:2 by weight because higher ratios produce lower strengths and excessive segregation of sand in the grout mixture may occur. Mix proportions may be determined by Corps of Engineers Specifications CRD C615.

d. Physical Properties. For structural preplaced aggregate concrete where strength and other physical properties are a consideration, the grout should be proportioned and test specimens, using the contemplated coarse aggregate grading, should be made to determine the grout mix proportions which will produce preplaced aggregate concrete of the required physical properties. Such tests will also provide information as to the quantity of materials needed for the work. Where necessary, the information on physical properties of the structural preplaced aggregate concrete should include strength, resistance to freezing and thawing exposure, modulus of elasticity, drying shrinkage, volume change, or other structural criteria. Physical properties of preplaced aggregate concrete made with a grout containing pozzolan and a fluidifier have been determined and compared with conventional concrete in a number of laboratory tests. This data can be found in published reports (U.S. Army Engineer, WES, 1954) (U.S. Bureau of Reclamation, 1949).

Compressive strength of concrete with a given maximum size aggregate, grout fluidifier, and pozzolan is slightly lower at 28 days' age than that of conventional concrete containing entrained air and an equal amount of cementing materials. At 90 days' age and later, its strength is equivalent to that of conventional air entrained concrete (U.S. Army Engineer, WES, 1954). Concrete containing aluminum powder or a grout fluidifier, and pozzolan develops a higher bond strength with old concrete than does new, conventional concrete. This may be explained because of the greater fluidity of the grout as compared with mortar and the expansion of the grout which develops a slight pressure during the formation of the hydrogen gas.

e. Placement.

(1) Foundation Preparation. Foundation preparation is important in underwater placement. For example, if extremely fine material is left on the foundation or in heavy suspension just above the foundation, it will be displaced upward into the aggregate. The dispersed fine material then coats the aggregate or settles and becomes concentrated in void spaces in the aggregate, thus precluding proper intrusion and consolidation. Therefore, all loose fine material must be removed insofar as possible before placement of aggregate. Alternatively, if structural conditions permit, a layer of sand and gravel may be first deposited to serve as a filter bed to prevent contamination of preplaced coarse aggregate.

(2) Aggregate Placement. Coarse aggregate should be washed and screened immediately before placing in the forms so that it will be surface

moist at the time of grout injection. Dry aggregate will absorb water from the grout which thickens the grout within the aggregate mass and may result in ungrouted or honeycombed areas. If more than one size of coarse aggregate is used, the aggregate should be weighed, batched, and mixed in the proper proportions, or discharged at proportional rates onto the wash screen. The wash screen may be either a vibrating deck or revolving type. The latter is effective as a blender, as well as a washer.

For structural concrete work, aggregate is commonly conveyed to the forms in concrete buckets. A flexible rubber elephant trunk is often used to limit the height of free fall, thus preventing segregation, and for placing in constricted areas. The total fall distance and method of handling should be such that segregation and aggregate breakage are reduced to a minimum. Permissible fall distance depends on aggregate size and soundness. Where coarse aggregate is being placed through water in mass concrete work, as in bridge piers, it may be discharged directly into the forms from bottom dump barges or self-unloading ships. Coarse aggregate has been placed successfully to depths of well over 30.5 meters (100 feet) in water where the possibility of breakage is eliminated (Davis and Haltenhoff, 1956). While some segregation may occur, segregation itself is not usually objectionable since it tends to result only in a somewhat greater void content and a non-uniform distribution of the void system throughout the aggregate mass, the result being to increase, slightly, the grout requirements with an insignificant effect on the strength of the mass concrete. However, an accumulation of smaller sizes might reduce the void size sufficiently to preclude consolidation within the area by the grout.

(3) Grout Quality Control. The pumpability of grout is controlled by the consistency test, using a standard flow cone in accordance with Corps of Engineers CRD C611. To maintain uniformity, time of outflow should be limited to between 18 and 22 seconds. However, grouts can be successfully pumped having an outflow of up to 30 seconds, depending on void content of the aggregate. Test cylinders should be made in accordance with Corps of Engineers Specification CRD C84 and tested in accordance with appropriate ASTM standards.

f. Curing. Curing should be in accordance with accepted conventional concrete practice. As with any concrete, extended periods of wet curing beyond the usual 7 days will be beneficial in improving the quality of the concrete.

3. Portland Cement Grout.

a. Types and Characteristics. Portland cement grout has a variety of uses in coastal structures and is similarly varied in its makeup. A simple combination of cement and water, in a flowable consistency, is sometimes used to fill joints and voids in concrete, masonry, or rock. More often other materials are added to improve various properties or reduce cost. These include sand and clay, used as inert fillers, and colloidal clays such as bentonite to stabilize fresh grout placed under water. Also included are special purpose admixtures to increase strength, retard or accelerate set and strength gain, cause expansion of the grout, prevent shrinkage, or improve bond, penetration, impermeability, plasticity, or resistance to freeze-thaw damage or chemical attack. These are discussed more fully in

Section V, Portland Cement Concrete, and in the previous discussion of preplaced aggregate concrete. In some cases the desired properties can be satisfactorily obtained by using one of the previously described special types of Portland cement.

b. Mixes. Where grout can be pumped or poured into relatively open joints or voids a mixture of one part cement to typically three or four parts sand is common, with just enough water for satisfactory placement. For very large voids, gravel may also be added. Where the material will be pumped into the ground to raise a settled slab or behind a bulkhead to plug a hole or break, a mixture of clay or silt with about 10 percent cement can sometimes be used. For filling or repairing narrow joints or cracks a neat cement grout consisting of 1 part cement mixed with 1 to 10 parts water to obtain proper consistency, may be appropriate. In some cases the use of an admixture may be justified to enhance certain properties. In such a case care should be taken to ensure the suitability of the admixture for the conditions and materials involved, and that dosage and mixing are correct. Pertinent Corps of Engineers Specifications include CRD C615, CRD C619, CRD C611, and CRD C612.

c. Placement Methods and Effects. Portland cement grout is usually placed by one of the following methods:

(1) Dumping or pouring into large voids or onto flat or sloping surfaces;

(2) free discharge from a hose or tremie trunk, above or under water, into a form or into voids or cavities in rock, masonry, or concrete;

(3) pressure discharge from a hose or pipe;

(a) into soil to correct settlement of a slab or light foundation by displacement or "mud jacking," or behind a bulkhead for sealing or patching; or

(b) into cracks or joints in concrete, masonry, or rock; and

(4) hand placement by pouring or "dry packing."

Where grout is used to fill joints, cracks or cavities in structural members it will be important to avoid or minimize shrinkage. This will require the best practicable combination of compaction, low water-cement ratio, and possibly the use of an expanding or plasticizing admixture in the grout. If a significant surface area of freshly placed grout is exposed to the air, especially when the grout has a high cement factor, the surface will need to be kept continuously moist for several days if shrinkage cracks are to be avoided.

If the grout is injected into a confined space, such as immediately behind a bulkhead or into cracks or cavities, caution must be used to avoid building up excessive pressure which could displace or rupture the confining structure. This can be avoided by carefully limiting the injection pressure,

or by grouting in properly sized increments or lifts and allowing adequate setting time between them. Tests for the setting time of grout are described in Corps of Engineers Specification CRD-C614.

d. Effects of the Environment. Portland cement grout will be affected to varying degrees by the environmental conditions and forces acting on the concrete, masonry or rock with which it is associated. Placed in thin joints or cracks it will have some protection from wave action, abrasion, periodic wetting and drying, and fire but may be vulnerable to water penetration, freeze-thaw cycles, chemical attack and seismic forces. Where used for surface repair, topping or void filling it may be exposed to all these. Most of these environmental forces will be adequately resisted by a grout having an optimum combination of strength, impermeability, entrained air content, and freedom from excessive shrinkage. Where a certain type of exposure is likely to be severe, the added cost of a beneficial proprietary admixture may be warranted. .

e. Functions in Coastal Structures. The many uses of Portland cement grout can be broadly classified as follows:

(1) In protective structures:

(a) filling voids in rock revetments; (this may be for improved slope stability, erosion resistance against waves, currents or floating debris, or rat-proofing);

(b) filling joints in precast block revetments; or

(c) sealing voids in stone breakwaters to improve wave attenuation. (This should be undertaken very judiciously, lest it cause excessive pressure buildup in the breakwater structure under heavy wave action, or trap and amplify resonant wave energy within the protected water area).

(2) In functional structures:

(a) grouting cyclopean or preplaced aggregate concrete;

(b) setting steel piling or tieback anchors in rock; and

(c) filling voids in hollow masonry walls.

(3) In structural repairs:

(a) repairing spalled, broken or cracked concrete;

(b) plugging breaks or holes in steel or concrete bulkheads; and

(c) correcting foundation settlement.

4. Soil Cement.

a. Description of Soil Cement. Soil cement is a mixture of pulverized soil and measured amounts of Portland cement and water, compacted to a high

density. As the cement hydrates, the mixture becomes hard and increases the stability of the soil.

The term "soil" includes native soils, gravels, sands, crushed materials, and miscellaneous materials such as cinders, slag, caliche, and chert.

b. Types of Soil Cement. There are three general types of soil cement mixtures depending on the quantity of cement and water added to the soil.

(1) Compacted Soil Cement. This mixture contains sufficient cement and moisture for maximum compaction. It will withstand laboratory freeze-thaw tests (ASTM Standard D560, CRD C594) and wet-dry tests (ASTM Standard D559, CRD C593) and will meet weight loss criteria.

(2) Cement-Modified Soil. This is an unhardened or semihardened mixture of soil and cement. When relatively small quantities of cement and moisture are added to a soil, the chemical and physical properties of that soil are changed. The soil's plasticity and volume change capacity are reduced and its bearing value increased. In cement-modified soil, only enough cement is used to change the physical properties of the soil to the desired degree--less cement than is required to produce a hard soil-cement. The use of cement to produce a cement-modified soil can be applied to both silt-clay and granular soils to increase the bearing values and reduce plasticity of soil materials.

(3) Plastic Soil-Cement. This is a hardened mixture of soil and cement that contains sufficient water, at the time of placing, to produce a consistency similar to that of plastering mortar. Plastic soil-cement is used to line or pave steep or irregular slopes for erosion control of banks and ditches.

c. Mixing Soil Cement. Since soil-cement obtains its stability primarily by the hydration of cement and not by cohesion and internal friction of the materials, practically all soils and soil combinations can be hardened with Portland cement. The general suitability of soils for soil-cement can be judged, before they are tested, on the basis of their gradation. On the basis of gradation, soils for soil-cement can be divided into three broad groups.

(1) Sandy and Gravelly Soils. Sandy and gravelly soils with about 10 to 35 percent silt and clay have the most favorable characteristics and generally require the least amount of cement for hardening if they contain 55 percent or more passing No. 4 sieve. These soils are readily pulverized, easily mixed, and can be built under a wide range of weather conditions.

(2) Sandy Soils, Deficient in Fines. Soils such as some beach, glacial, and windblown sands make good soil-cement, although the amount of cement needed for adequate hardening may be higher than the first group.

(3) Silty and Clayey Soils. These soils make satisfactory soil-cement, but those containing high clay contents are harder to pulverize. Generally, the more clayey the soil the higher the cement content required to harden it gradually.

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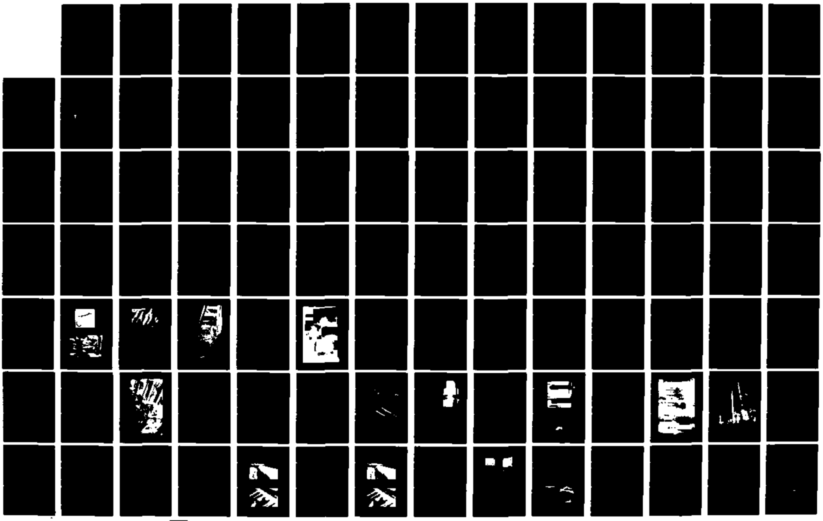

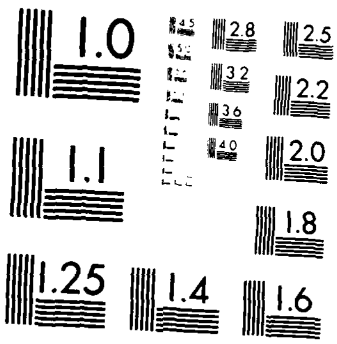

MICROCOPY RESOLUTION TEST CHART

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Excessivly wet soil is difficult to mix and pulverize. Experience has shown that cement can be mixed with sandy soils when the moisture content is as high as 2 percent above optimum. For clayey soils the moisture content should be below optimum for efficient mixing.

d. Curing. Compacted and finished soil-cement contains sufficient moisture for adequate cement hydration. A moisture-retaining cover must be placed over the soil-cement soon after completion to retain this moisture and permit the cement to hydrate. Materials such as waterproof paper or plastic sheets, wet straw or sand, wet burlap or cotton mats are entirely satisfactory.

e. Engineering Properties of Soil Cement. During construction the soil-cement is compacted to a high density. As the cement hydrates, the mixture hardens in this dense state to produce a structural slablike material, and thus possesses engineering properties. The magnitude of these properties depends primarily on the type of soil, age and curing conditions.

Depending on soil type, 7-day compressive strength of saturated specimens of the minimum cement content meeting soil-cement criteria is generally higher than 2.1 megapascals (300 pounds per square inch). The 28-day flexural strength is approximately 20 percent of the compressive strength, and the modulus of elasticity about 6 900 megapascals (1 million pounds per square inch). Soil cement tends to be brittle, cracking under impact and temperature stresses.

f. Functions of Soil-Cement. Soil-cement is used primarily as a base course for stabilizing and compacting soils for foundations, bank protection and subbase construction. It has been used for earth dam cores, reservoir linings, and slope protection.

5. Sulfur Cement Concrete and Grouts.

a. Introduction. The past 15 to 20 years have seen a rapid increase in research and development work on sulfur, and two factors have been the cause of this increase. In the early 1960's, large quantities of sulfur were beginning to be recovered from sour natural gas and petroleum. Sulfur producers realized the necessity of creating new end-use markets to absorb this sulfur, and sponsored research to that purpose. As a result of this research, sulfur was discovered, or in some cases rediscovered, to have a number of interesting mechanical properties. Research workers who originally had envisioned sulfur as a substitute material now discovered that sulfur had properties superior to some conventionally used materials and that it could outperform such material both technologically and economically. These initial discoveries stimulated additional research in many aspects of sulfur. Many interesting new uses for sulfur in construction have been discovered. Some of the more promising are:

(1) Sulfur asphalt paving materials,

(2) sulfur concretes,

(3) sulfur coatings,

(4) impregnating materials with sulfur, and

(5) foamed sulfur.

The acceptance of sulfur asphalt technology by highway departments and contractors has been due not only to the desire to replace asphalt by readily available sulfur, but also to the fact that the sulfur asphalt materials have shown improved properties compared to asphalt, and to the fact that sulfur asphalt permits the use of aggregates which would be unsuitable for use with asphalt.

It has been known for many years that mixing molten sulfur with sand or aggregate produces a sulfur concrete with excellent strength. However, the durability of simple sulfur concretes of this type has not been impressive, particularly under conditions of high humidity and wide temperature fluctuation. Research has centered on developing additives to sulfur to improve the durability. Work carried out by the U.S. Bureau of Mines at Boulder City, Nevada, and by Sulfur Innovations, Ltd., Calgary, Alberta, has resulted in sulfur concretes with greatly improved properties.

Porous materials can be impregnated with molten sulfur that, on solidifying, imparts additional strength to the materials. Resistance to freeze-thaw cycles and corrosion is also frequently improved by sulfur impregnation. Recent research indicates that with suitable additives, sulfur could be made into a rigid foam having excellent mechanical and insulating properties. The properties of sulfur-based construction materials generally equal or surpass those of conventional cementing materials.

b. Sulfur-Asphalt (SA) Materials. Basically, all the SA technologies involve combining molten sulfur and hot asphalt to produce a sulfur-asphalt binder, which is then mixed with mineral aggregate to give a SA hot-mix paving material. The individual technologies differ in the method and equipment used to produce the SA binder.

(1) Mixes. Depending on the technology and type of aggregate used, from 1/3 to 1/2 by weight of the asphalt can be replaced by sulfur. Because sulfur is about twice as heavy as asphalt, sulfur-asphalt binders have higher densities than normal asphalt. Because a certain volume of binder is needed to obtain an acceptable void content of the compacted paving material, optimum stability of SA paving materials generally occurs at a somewhat higher binder content (by weight) than when straight asphalt is used. In practice, between 6.2 and 8.9 newtons (1.4 and 2 pounds) of sulfur are needed to replace 4.4 newtons (1 pound) of asphalt. Because SA paving materials are three-component systems (sulfur-asphalt-aggregate) they permit more flexibility of design than with regular two-component (asphalt-aggregate) paving materials.

When hot asphalt and sulfur are mixed, some of the sulfur, about 20 percent by weight of the asphalt, will dissolve in the asphalt. The remainder of the sulfur forms a dispersion of sulfur in asphalt. Both the dissolved and the dispersed sulfur modify the properties of the asphalt.

Some of the dissolved sulfur reacts chemically with the asphalt to form polysulfides, which make the asphalt softer and more ductile. (At higher

temperatures, above 160° Celsius, dehydrogenation occurs with the formation of hydrogen sulfide (H_2S) and harder, more viscous asphalts. This type of reaction is undesirable, and is one of the reasons why temperature control is important in SA technology.)

The dispersed sulfur is present as droplets, most of which are below 5 micrometers in size. These solidify as the paving material cools below the melting point of sulfur (120° Celsius), and the resulting solid sulfur phase imparts increased structural strength to the SA paving material.

(2) Properties. Listed below are some of the improved properties of SA paving materials:

(a) The strength of SA, as measured by the Marshall method, can be designed to be considerably higher than that of regular asphalt;

(b) the increased strength obtainable with SA may permit the use of lower quality aggregates or a reduction in paving thickness;

(c) SA increases the high temperature stiffness of paving materials, without a corresponding increase at low temperatures, thus softer asphalts can be used to minimize winter cracking, with less danger of deformation at summer temperatures;

(d) SA has a lower viscosity than regular asphalt and can be mixed at lower temperatures, resulting in reduced energy consumption at the hot-mix plant;

(e) SA improves resistance to water stripping (the breaking of the bond between asphalt and aggregate by a layer of water that forms on the surface of some types of aggregates), thus aggregates which would otherwise be unsuitable can be used, and the use of antistripping agents can be reduced or eliminated;

(f) resistance to gasoline, diesel fuel and other solvents is improved; and

(g) stress fatigue characteristics are improved.

Not only are many of the properties of SA superior to other concrete binder mixes, but also some of these properties may be enhanced by combinations of SA with other materials. The combination of sulfur-asphalt and a nonwoven fabric results in a high performance product that has high tensile strength, is capable of withstanding considerable deformation without breaking, and remains waterproof even when placed on sharp aggregate. The lower viscosity of SA improves the impregnation of the fabric and the ductility of SA improves the fabric's low temperature performance. On solidification, the finely dispersed sulfur particles impart additional strength to the impregnated fabric.

(3) Placement. The SA hot-mix is handled like regular asphalt hot-mix paving material. Equipment and technology for transporting, placing, and

compacting the SA material is identical to that used for regular asphalt hot-mix.

c. Sulfur Concrete. During the past 5 years, interest in sulfur concrete (SC) has grown rapidly. Research and development on SC is currently being carried out by at least 50 companies and agencies, some of which are now actively marketing SC products and materials.

Sulfur concretes are basically simple materials, made by mixing sulfur plus certain additives with heated mineral aggregates. On cooling, SC sets to give a high-strength material with superb corrosion resistance. Early attempts to make and use SC date back more than 100 years. However, current SC technology is a product of the 1960's and 1970's following the discovery and development of suitable additives or "plasticizers" for the sulfur which impart durability to SC. A considerable number of compounds have been screened as additives. Currently, the most popular ones are dicyclopentadiene (DCPD), dipentene (DP), certain proprietary polymeric unsaturated hydrocarbons, and combinations of these materials. Much of the current research work is concentrated on finding additives or combinations of additives which will further improve the durability and performance of SC.

Sulfur concretes can be designed to have compressive and tensile strengths twice or more those of comparable Portland cement concretes (PCC), and full strength is reached in hours rather than weeks. Sulfur concretes are extremely corrosion resistant to many industrial chemicals, including most acids and salts. Sulfur concrete is highly resistant to saltwater, and marine applications may be attractive.

(1) Additives. While satisfactory SC had been obtained by the addition of 5 percent DCPD as a modifier to the sulfur, recent U.S. Bureau of Mines work indicates that a superior product can be obtained by the use of mixed modifiers. These consist of a mixture of DCPD fractions from DCPD manufacture containing three, four, or more units of cyclopentadiene or methylcyclopentadiene per molecule. Several companies market materials of this type. The relative amounts of DCPD and oligomer used in the modifier will vary to some extent with the type of aggregate, but a mixture of 65 percent DCPD and 35 percent oligomer is about optimum in most cases. Five percent by weight of this mixed modifier is added with stirring to the molten sulfur at 130° Celsius, and allowed to react with it for several hours. To ensure complete reaction of the sulfur with the modifier, the U.S. Bureau of Mines allows the mixture to react for 24 hours, but there are indications that this time can be shortened considerably.

The use of mixed modifier rather than straight DCPD results in improved durability and corrosion resistance. It is also easier to prepare the modified sulfur using the mixed modifier. The reaction of DCPD with sulfur is exothermic, and care must be exercized when adding straight DCPD to molten sulfur to prevent overheating. With mixed modifiers, the reaction is easier to control.

(2) Aggregates. A metallurgist at the U.S. Bureau of Mines (W.C. McBee, Boulder City Laboratory, personal communication, 1981) stressed that each aggregate system must be analyzed and evaluated as to its suitability for SC. Generally, limestone aggregates tend to give SC higher strength

and freeze-thaw resistance, whereas quartz aggregates give higher corrosion resistance. The salts in chloride and sulfate-containing aggregates have no effect on bonding, but some aggregates are unacceptable for SC because they react chemically with the binder. Aggregates containing swelling clays are also undesirable.

(3) Mix Proportions. Design is normally for maximum compressive strength, and based on the VMA (voids in mineral aggregate) procedure. Optimum strength generally coincides with maximum workability and minimum voids level. Coarse and fine aggregates blended to give about 25 percent VMA were found to be optimal. In the finished SC, 4 to 5 percent voids remained. These voids are not interconnected, and moisture absorption by SC is very low, 0.05 percent or less, whereas PCC often absorbs 3 percent or more. This is an important factor in the resistance of SC to corrosion.

Aggregate grading according to ASTM specification is unsatisfactory for SC. From 6 to 10 percent of fine (200 mesh) material should be included to provide good workability. To prevent dusting, the fine material can be mixed with the modified sulfur before it is added to the heated aggregate in the mixer.

(4) Properties and Uses. The quick curing characteristics of SC make the material attractive in many situations. Eighty percent or more of final strength is reached within a few hours of pouring, compared to several weeks for PCC. Moreover, SC will cure equally well under freezing conditions, which are highly detrimental to PCC curing. SC can tolerate chloride and sulphate-containing aggregates found in desert areas, because the bonding properties of sulfur are not affected by salts. The good heat insulation characteristics of sulfur and the elimination of water in the manufacturing process are two additional advantages of SC in desert areas (The Sulphur Institute, 1979).

(a) Fire Effects. The inherent flammability and low melting point of sulfur impose some limitations of SC use. Flammability can be controlled to some extent by the use of additives, and it is fortunate that the DCPD types of additives used to improve the durability of SC also impart a degree of fire resistance. Sulfur concretes are in any case considerably less of a fire hazard than wood. Because of the low thermal conductivity, heat penetration is slow, and SC can survive short exposures to fire without serious damage. Sulfur concretes do not support combustion, and flame spread is essentially zero.

(b) Structural Use Limitations. The low melting point of sulfur limits the use of SC in applications where loss of structural strength in event of a fire could be catastrophic. Thus, SC for load-bearing structures will probably not be used in high-rise apartment buildings. However, the properties of SC appear to make it fully acceptable for single-story dwellings, as well as for utility buildings and a wide range of prefabricated structures. These materials are well suited to specific uses in the coastal zone environment, and when used in a restricted manner may resist coastal environments for many years.

6. Environmental Considerations.

a. Corrosive and Pollutant Attacks on Exposed Surfaces.

(1) Bituminous Asphalt. Bituminous asphalt is stable in the presence of nearly all chemically-laden substances; however, because asphalt is refined from petroleum-based products, exposure to petroleum solvents will cause deterioration and disintegration of asphalt. It is normally unaffected by usual concentrations (less than 1 normal) of acids, salts and other waste materials.

(2) Preplaced Aggregate Concrete. Preplaced aggregate concrete, like Portland cement concrete, is rarely attacked by solid, dry chemicals. Corrosive chemicals must be in some minimum concentration and usually are sulfates or acids. Also organic acids such as acetic, formic, and lactic can be quite destructive to preplaced aggregate concrete.

(3) Portland Cement Grout. This grout is attacked by the same chemicals as Portland cement concrete; however, if the grout is not of equal density as concrete then the chemical attack may be more aggressive.

(4) Soil Cement. Soil cement in its normal use is not attacked by most chemicals except for natural occurring sulfates such as sodium, potassium, and calcium.

(5) Sulfur Cement and Grout. Sulfur cement and grout are not generally affected by pollutants in the coastal or marine environment and they can tolerate chloride and sulfate-containing aggregates. They are highly resistant to the corrosive effects of saltwater (The Sulphur Institute, 1979).

b. Sunlight Exposure Effects.

(1) Bituminous Concrete. Bituminous concrete weathers only at the surface when exposed to sunlight and air. The weathering results in the very slow evaporation of solvents near the exposed surface, but because of the impermeability of asphalt the solvent loss is very slow.

(2) Preplaced Aggregate Concrete. This concrete is not affected by sunlight when properly protected from evaporation of mixing water during the curing period.

(3) Portland Cement Grout. This grout is not affected by sunlight.

(4) Soil Cement. Soil cement is not affected by sunlight.

(5) Sulfur Cement Concrete and Grout. Sulfur cement concrete and grout does not appear to be affected by sunlight; however, being a relatively recent material development, experience is limited.

c. Water Penetration Effects.

(1) Bituminous Concrete. This concrete is highly resistant to water penetration because of the impermeability of asphalt. Formulations

can be used in porous structures; however, the asphalt does not deteriorate in the presence of water unless accompanied by petroleum solvents.

(2) Preplaced Aggregate Concrete. This concrete is not normally penetrated by water, but seawater with a high sulfate and chloride content may be moderately aggressive as on Portland cement concrete.

(3) Portland Cement Grout. Portland cement grout will undergo the same environmental effect as preplaced aggregate concrete.

(4) Soil Cement. Soil cement will not be affected by water penetration.

(5) Sulfur Cement Concrete and Grout. Sulfur cement concrete and grout will not be affected by water penetration.

d. Wave and Current Effects.

(1) Bituminous Concrete. Bituminous concrete is not affected by normal waves and currents unless they have sufficient force to carry suspended matter to cause severe abrasion. The abraded asphalt particles are a stable compound and sufficiently diluted as to not cause any measurable impact on the adjacent environment.

(2) Preplaced Aggregate Concrete. Preplaced aggregate concrete exhibits no effects from waves and currents.

(3) Portland Cement Grout. Portland cement grout also exhibits no effects from waves and currents.

(4) Soil Cement. Soil cement should not be used in a wave and current environment as it is brittle and subject to damage by wave impact.

(5) Sulfur Cement Concrete and Grout. Sulfur cement concrete and grout exhibits no direct effect due to waves and currents. Wear by abrasion and cavitation can result from severe wave action.

e. Effect of Severe Temperature and Ice.

(1) Bituminous Concrete. Bituminous concrete may be either a hot-mix or cold-mix design. When mixing temperature should be only sufficient to ensure dry aggregate but in no case should it exceed 163^{o} Celsius (325^{o} Fahrenheit). Exposure to higher temperatures will cause solvents to dissipate resulting in deterioration of the asphalt concrete. Ice does not affect bituminous concrete; however, severe cold temperature will cause the concrete to become brittle.

(2) Preplaced Aggregate Cement. Preplaced aggregate cement is generally not affected by severe temperatures. Air-entraining admixtures will further improve resistance to freezing and thawing as in Portland cement concrete.

(3) Portland Cement Grout. Portland cement grout is also highly resistant to the effects of severe temperatures. Like preplaced aggregate

cement, its resistance can be further enhanced with addition of air entraining admixtures.

(4) Soil Cement. Soil cement is seldom exposed to severe temperatures and ice as these conditions require an increase in cement content resulting in a substantial increase in cost and may eliminate the consideration of soil cement as a construction element in this environment. For severe exposures it is important to note that an excess of cement is not harmful but that a deficiency of cement will result in inferior soil-cement resulting in cracking and spalling.

(5) Sulfur Cement Concrete and Grout. Sulfur cement concrete and grout because of the low melting temperature of sulfur (130^{o} Celsius) will deteriorate at elevated temperatures. Low temperatures have little effect on this material.

f. Marine Organisms.

(1) Bituminous Concrete. Bituminous concrete is subject to deterioration from crustaceous organisms as it is comparatively soft as a coastal environment construction material. When used as a binder with other materials such as large stone, this type of deterioration has little effect on the structure.

(2) Preplaced Aggregate Concrete. Preplaced aggregate concrete is not affected by marine organisms.

(3) Portland Cement Grout. Portland cement grout is not affected by marine organisms if properly mixed and placed.

(4) Soil Cement. Soil cement is not usually exposed to an environment containing marine organisms. When it is, many organisms will become attached to the rough surface of an exposed soil cement surface and cause spalling. Boring animals can penetrate the surface but apparently do not find it a desirable environment; therefore it is not a common condition.

(5) Sulfur Cement Concrete and Grout. Sulfur cement concrete and grout has not shown any deterioration from marine organisms; however, due to the limited experience with this material, long-range performance experience is not available.

g. Periodic Wetting and Drying.

(1) Bituminous Concrete. Bituminous concrete surfaces may tend to develop fine cracks or alligator patterns on exposed surfaces when subjected to alternated wetting and drying. Such cracks seldom develop any signficant depth in asphalt concrete and are not serious in coastal structures

(2) Preplaced Aggregate Concrete. Preplaced aggregate concrete is subject only to the same action as Portland cement concrete, i.e., the formation on the surface of "D cracks" usually in random patterns. These are normally restricted to the surface and do not contribute to serious deterioration.

(3) Portland Cement Grout. Portland cement grout will react similarly to preplaced concrete.

(4) Soil Cement. Soil cement may be exposed to alternate cycles of wetting and drying; however, because of the nature of this material it tends to harden until all the cement content is fully hydrated. Sufficient experience is not available to predict the long-term effects; however, because of the hardened condition improved resistance to wetting and drying is a reasonable expectation.

(5) Sulfur Cement Concrete and Grout. Sulfur cement concrete and grout is unaffected by periodic wetting and drying.

h. Wind Erosion. None of the five materials discussed in this section are subject to change or deterioration by wind. Strong winds may pick up sand particles that may cause some etching of their exposed surface over extended periods of time.

i. Effects of Burrowing Animals.

(1) Bituminous Concrete. Bituminous concrete, being a petroleum-base product, is an inhibitor to animals. It contains no food value and therefore is unaffected by animals.

(2) Preplaced Aggregate Concrete and Portland Cement Grout. Preplaced aggregate concrete and Portland cement grout (as in Portland cement concrete) are very hard materials and not disturbed by burrowing animals.

(3) Soil Cement. Soil cement used primarily to stabilize soil, is not as hard a material as Portland cement concrete. It can be attacked by burrowing animals but because of the shape and mass of these structural elements (foundations), usually any damage is minor and insignificant.

(4) Sulfur Cement Concrete and Grout. Sulfur cement concrete and grout is also hard and resistant to activities of burrowing animals. The sulfur content is also a deterrent.

j. Effects of Flora. There are no reports of flora growth having any effect on any of the five materials discussed in this section.

k. Fire.

(1) Bituminous Concrete. Bituminous concrete, because of its petroleum-base content, is subject to serious damage by fire. However, because the asphalt binder in this concrete contains very little solvent, it does not normally sustain burning itself.

(2) Preplaced Aggregate Concrete and Portland Cement Grout. Preplaced aggregate concrete and Portland cement grout are resistant to fire and extreme high temperatures.

(3) Soil Cement. Soil cement is fire resistant.

(4) Sulfur Cement Concrete and Grout. The inherent flammability and the low melting point of sulfur (130° Celsius) results in the loss of structural strength, causing the immediate deterioration of a structure.

l. Abrasion.

(1) Bituminous Concrete. Bituminous concrete has a substantial resistance to wearing away by rubbing and friction. Not being as hard a material as Portland cement concrete or steel, it is not highly resistant to severe impact by large particles; however, it has a high degree of resistance to normal sand or wind abrasion. Precise limits for abrasion resistance are not possible to determine and it is usually best to rely on an analysis of specific environmental conditions to evaluate the physical properties of the designed bituminous concrete to be used.

(2) Preplaced Aggregate Concrete and Portland Cement Grout. Preplaced aggregate concrete and Portland cement grout are subject to abrading or etching by wind or waterborne particles; however, the slow rate of the abrasion process in the coastal zone is usually unnoticeable. Abrasion of structures above the water surface may result in some minor dusting problem.

(3) Soil Cement. Soil cement when used as an integral part of a foundation, is not subject to abrasion. When used as a surface stabilizer it will wear quite readily, if subjected to surface traffic, and result in increased dusting.

(4) Sulfur Cement Concrete and Grout. Sulfur cement concrete and grout have a relatively high resistance to abrasion. It is believed that admixtures can enhance these properties. Because of the short field experience of this relatively new material, research and testing is still underway to develop admixtures that can improve abrasion resistance properties of this material.

m. Seismic Effect.

(1) Bituminous Concrete. Bituminous concrete, not being a structurally rigid material, does not resist seismic forces or movement of the earth. Instead, its properties of plasticity and the ability of asphalt to flex allow it to move with a seismic event and thus reduce the possible damage to structures.

(2) Preplaced Aggregate Concrete and Portland Cement Grout. Preplaced aggregate concrete and Portland cement grout resistance to seismic effects is primarily a design problem. Severe seismic forces can cause structural failure by direct structural damage or by altering the foundation condition, resulting in structure settlement and failure or deterioration.

(3) Soil Cement. Soil cement in its use in coastal structures is usually unaffected structurally by seismic activity, but it may shift with earth movement resulting from seismic-induced stress.

(4) Sulfur Cement Concrete and Grout. Sulfur cement concrete and grout resistance to seismic effects is similar to that of Portland cement

concrete. Seismic forces can cause structure failure by producing excessive stress in the material, resulting in structural deterioration.

n. Human Activity. Human activity has very little impact on structures of these materials except where visual impact may be noticeable resulting from graffiti or other defacing action.

7. Uses In Coastal Structures.

a. General.

(1) Bituminous Concrete. Bituminous concrete is used to perform three basic functions in coastal construction. It is used as a binder or filler to stabilize quarrystone work or soils, as a sealant to prevent the migration or flow of liquids, and, in its asphaltic cement form, as a wearing surface that can be easily repaired or replaced as it is eroded. Bituminous materials are also used in the preservative treatment of wood as discussed in Section VIII, Wood.

(2) Preplaced Concrete. Preplaced concrete is usually used in large dimension mass concrete structures when aggregate larger than can be conveniently handled by ordinary mixing methods is desired.

(3) Portland Cement Grout. Portland cement grout is used generally as a filler and binder for quarrystone work and as a stabilizer for soils.

(4) Soil Cement. Soil cement is used to strengthen foundation soils and to resist erosion of selected layers of soil.

(5) Sulfur Cement and Grout. Sulfur cement and grout are resistant to many environmental attacks in the coastal zone and may become economical to use due to an increasing abundance. Because of limited general use and history, sulfur cement and sulfur asphalt must be considered unproven materials. However, the property of reaching full strength on cooling could be especially useful in making repairs to structures and embankments where the cost of delay is high. In busy cargo terminals, on heavily used roads or in coastal structures subject to imminent assault by storms, quick repairs to structures not immersed in water could be made. No practical techniques for placing sulfur concrete under water have been developed to date. (Fast cooling is the problem.)

b. Offshore Structures.

(1) Bituminous Concrete. Bituminous concrete is used for reinforcement or grout to fill and plug the voids in stone or rubble-mound breakwaters. The binding action of the mastic tends to produce a large firm mass while being flexible enough to conform to some differential settlement of the structure (Fig. 44.)

(2) Preplaced Concrete. An impermeable breakwater could be made by placing uniformly graded stones in layers along the contours of a rubble-mound breakwater. Each layer would be bound together with tremie-placed Portland cement concrete grout. The resulting mass concrete structure would be accomplished by the preplaced concrete method except that no forms would be used.

c. Shore-Connected Structures.

(1) Breakwaters, Jetties and Groins. Breakwaters, jetties and goins could be made in the same manner as offshore structures using bituminous concrete or preplaced aggregate methods.

(2) Seawalls.

(a) Bituminous Concrete. In addition to the types of uses described for offshore structures, bituminous concrete products and sealers may be required to make impermeable membranes, where required.

(b) Preplaced Concrete. Preplaced concrete techniques can be used for mass concrete seawalls. Forms for the vertical or specially contoured faces would be required. Otherwise, the placement methods would be as described for offshore structures except that a tremie may not be necessary for layers placed above the waterline. For good void filling, a vibrator would be used to ensure that the concrete grout flows into all the voids and fills the form.

(c) Portland Cement Grout. Portland cement grout would be used to fill synthetic mesh bags and tubes used to form seawall units.

(3) Revetments.

(a) Bituminous Concrete. Bituminous concrete is used to bind stone blankets together to form a stable mass or can be used by itself as slope protection, as shown in Figure 43.

(b) Portland Cement Grout. Portland cement grout may be used to bind stones in a blanket together to form a stable but brittle mass. It can also be pumped into weak soils to firm them for foundations or can be used to fill voids in earth layers to obtain foundation continuity.

(c) Soil Cement. Soil cement techniques may be used where the slope is composed of the right type of soil and the exposure is not subject to severe wave action. It has the advantage of not requiring aggregate materials to be hauled to the site.

(4) Piers and Wharves.

(a) Bituminous Concrete. Bituminous concrete wearing surfaces are sometimes used to provide an economical surface to be sacrificed to the wear of ordinary use. Replacement or refurbishment is easily and cheaply done and the underlying structure remains undisturbed.

(b) Preplaced Aggregate Concrete. Preplaced aggregate concrete has been used along the perimeter of landfills to act as a combination seawall, retaining wall, and wharf structure. Such structures are usually topped with a large reinforced concrete wall that supports the fender system and forms the "face of wharf."

VII. STRUCTURAL AND SHEET METALS

1. Types and Characteristics of Metals and Alloys.

a. Steel. Steel has been an important construction material for marine service since the late 1800's. Steel obtained this dominance at the expense of wood and iron because of greater strength and availability. Although other materials may have advantages, such as corrosion resistance, steel is relatively inexpensive, strong, and available in various shapes and sizes for marine application. To ensure the quality of the material used in construction, materials are purchased to specifications. ASTM standard specifications define the requirements to be satisfied by the particular material and indicate the procedure by which it may be determined that these requirements are met. ASTM Standard A6, "Standard Specification for General Requirements for Rolled Steel Plates, Shapes, Sheet Piling, and Bars for Structural Use," lists a number of specifications for materials that are suitable for marine application. Other ASTM specifications cover pipe, mechanical tubing, fittings, forgings, and other materials. ASTM specifications both from ASTM Standard A6 and other appropriate ASTM specifications for steel materials, suitable for marine application, are included in Appendix A.

(1) Metallurgy.

(a) Carbon Steel. Metallurgists define carbon steel as an alloy of iron and carbon with the carbon content under 2 percent. Structural steel specifications limit carbon to 0.35 percent or less for weldability considerations. Manganese is added to improve strength and toughness, but mostly to aid in the deoxidation of steel during refining and modify the detrimental effects of sulfur. Sulfur causes steel to be "hot short," i.e., to be brittle at high temperatures, which can lead to cracking during hot rolling and forging. Manganese combines with sulfur in the molten steel to form insoluable manganese sulfide, some of which is removed as slag, and the remainder as well distributed inclusions throughout the steel. The shape of these sulfide inclusions can be controlled by special processing during the steelmaking process. Phosphorous is also present as an impurity. Most steel specifications require the phosphorous content to be less than 0.05 percent because larger percentages of phosphorous cause a decrease of ductility and toughness, rendering the steel to be "cold short." Silicon is often added as a deoxidizing agent during the melting and refining of steel. Copper may also be present up to 0.25 percent.

(b) Carbon Steel Alloys. Depending on the alloy content, carbon steel can be classified as low, medium, or high alloy. Carbon steel contains only residual elements and elements, such as manganese and silicon, added during the melting and refining stage to obtain a workable product. Low alloy steel contains up to 1.5 percent of elements added to obtain increased strength or heat treatment capability. Medium alloy steel contains 1.5 to 11 percent added alloy elements. Above 11 percent alloy element content, the steel is classified as high alloy. The high alloy steels include both the ferritic and austenitic stainless steels.

(2) Processing.

(a) Deoxidation and Classification. Steels are classified on the basis of the amount of gases evolved during solidification. In the manufacture of steel from pig iron, excess carbon is removed by the exposure of the molten metal to oxygen or air until the desired carbon content is reached. Oxygen dissolves in the molten metal and reacts with carbon to form bubbles of carbon monoxide, which rise to the surface. Other sources of oxygen include that contained in materials added to the slag or molten metal and that present as a product of chemical reactions that occur during the steelmaking process. Because carbon and oxygen may continue to react during solidification, or the steel may have an unacceptably high oxygen content, deoxidation in the ladle of the molten steel may be required. The deoxidation practice, which may or may not be specified by the steel specification, is often an important consideration in choosing a steel for a particular application. Steels having decreasing degrees of gas evolution or deoxidation are termed "rimmed," "capped," "semikilled," and "killed." Figure 47 shows sketches of typical ingot cross sections corresponding to these degrees of deoxidation.

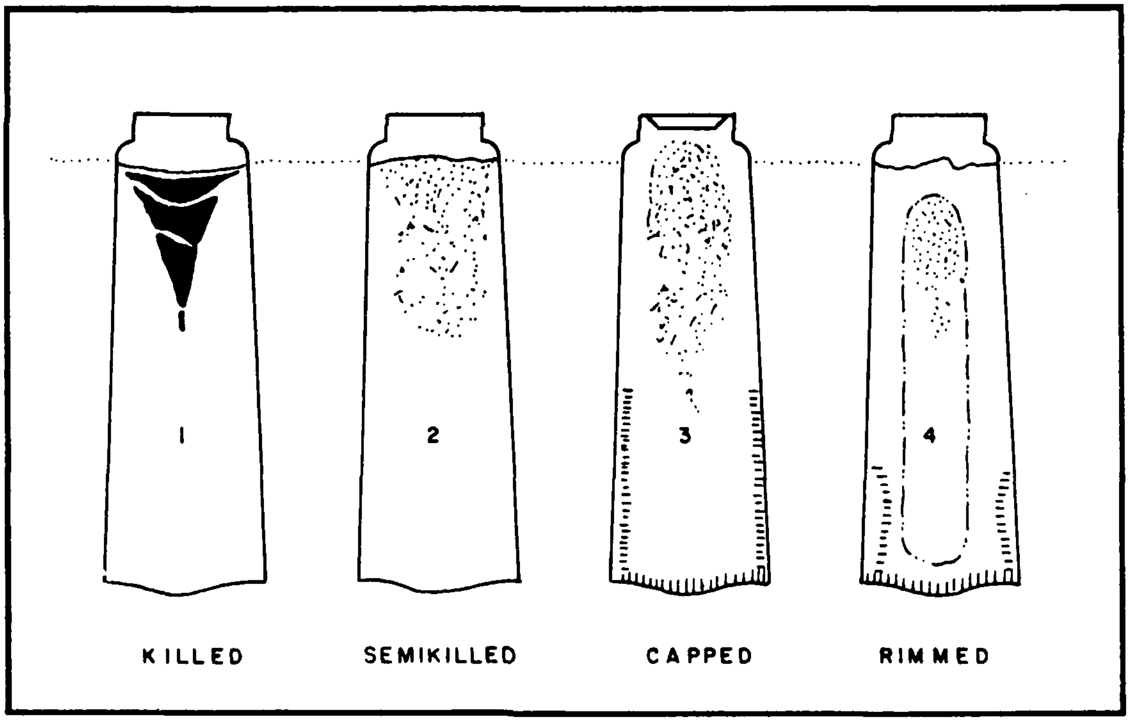


Figure 47. Typical ingot structures

Rimmed steels do not receive any silicon or aluminum deoxidation before being poured into ingots. Carbon and oxygen dissolved in the molten steel continue to combine forming small bubbles which effervesce during solidification. Some effervescence is also due to the much lower solubility of oxygen in solid steel compared to that in molten steel. Chemical composition

varies widely throughout rimmed steel ingots. The area near the surface is much lower in carbon, sulfur and phosphorus than the remainder of the ingot. This low carbon skin persists to the finished mill product which contributes to the superior deep drawing properties of rimmed steel.

Capped steel is similar to rimmed steel except that the effervescence of gas from the molten steel in the ingot mold is only allowed to occur for a minute or so before a cast-iron cap is placed on the mold. Capped steel has a thinner low carbon rim than rimmed steel but is of more uniform composition. Capped steel is used for plate, strip, pipe, trim plates, wire, and bars.

Semikilled steel is produced by additions of silicon and other deoxidation elements during the manufacture. These additions are carefully made in order to balance evolution of gases with solidification shrinkage. Semikilled steel is used for structural shapes, plate, pipe, forging billet and bars.

Killed steel is produced by the addition of excess deoxidizers over the amount required to fully remove all oxygen from the ladle. As the molten killed steel solidifies, a large shrinkage cavity forms, called the pipe, as shown in Figure 47. It is necessary to cut off the top of killed steel ingots at the bottom of the pipe to avoid producing a defect, known as a seam, in the rolled product. Killed steel is more uniform in both composition and mechanical properties than semikilled steel. However, because of the low yield of product per ingot, killed steel is more costly than semikilled steel.

The choice of deoxidizer used is often dictated by the specification chosen by the user after considering the end use. If high temperature use is contemplated (for instance for use in a steam boiler) silicon coarse-grain killed steel will be specified because of its improved resistance to deformation at high temperatures. When improved resistance to brittle failure is desired, particularly for service at temperatures below 20^{o} Celsius (68^{o} Fahrenheit), a silicon-aluminum dioxidation practice will be specified so as to produce a steel having a fine-grain structure. Vacuum degassing is also used when premium quality is required.

(b) Heat Treatment. Mechanical properties of steel can be altered by heat treatment. When steel is heated above a critical temperature (the specific temperature depends on the composition), transformation of the microstructure into a single phase solid solution occurs. This solid solution is called austenite. The temperature at which transformation takes place is called the austenitizing temperature. Steel heated to the austenitizing temperature and allowed to cool in the furnace to a temperature low enough for the steel to be handled is said to be annealed. Annealing is performed to reduce hardness, improve machinability, and facilitate cold working.

Normalizing is the process of heating the steel above the austenitizing temperature, allowing sufficient time for transformation to occur, and then removing the steel from the furnace and cooling in air. Normalizing is performed to refi .e grain size and homogenize microstructure, improve machinability, and or provide the desired mechanical properties. Normalizing

is usually performed on steels requiring additional heat treatment for hardening, on hot formed pressure vessel heads, and when specified by the applicable material specification.

Steels having sufficient carbon can be hardened by heating above the austenitizing temperature, holding at this temperature long enough for transformation to occur, removing the steel from the furnace, and immediately quenching it in water or oil. The resulting surface hardness depends on the carbon content, section size, and quenching medium. The depth of hardening depends also on alloy content and grain size. After quenching, steels are tempered by heating to a specified temperature (below the transformation temperature) and holding them at this temperature for a specified time, usually an hour per 2.54 centimeters of thickness. This process restores ductility. The particular tempering temperature used depends on the alloy content, mechanical strength requirements, and end use.

Low carbon steels are often stress relieved by heating between 593^{o} Celsius (1100^{o} Fahrenheit) and the austenite transformation temperature to remove resudial stresses resulting from prior forming or welding operations. Stress relieving restores ductility and toughness. It may also improve fatigue life. Welds areas are often postweld heat treated locally, i.e., stress relieved, using proprietary portable heating equipment.

(c) Alloy Additions. Alloying elements are added during the steelmaking process to improve mechanical properties or to improve corrosion resistance. Small additions, singly, of copper, nickel, chromium, silicon, and phosphorus have been shown to be effective in improving the corrosion resistance of steel. The greatest improvements in corrosion resistance are obtained by the addition of specific combinations of these alloying elements, such as specified by ASTM Standard A690 for H-piles and sheet piles intended for service in the splash zone. Other steels suitable for marine applications and having improved atmospheric corrosion resistance are ASTM Standards A242, A441, and A588.

Additions of chromium and molybdenum improve the high temperature oxidation resistance as well as improve the high temperature strength of steel. High-pressure steam tubes and piping are often 1.25 percent chromium alloy steel. Stainless steels meeting ASTM 400 series specifications include type 410, with 12 percent chromium, and type 430 with 18 percent chromium. However, because of a tendency to pit, the 400 series stainless steels are not recommended for marine service.

b. Aluminum.

(1) Alloy Strengthening. Aluminum, in high purity form, is soft and ductile but does not possess enough strength for most commercial applications. The addition of alloying elements, either singly or in combination, impart strength to the metal. Aluminum alloys can be classified into two catagories: nonheat-treatable and heat-treatable. The nonheat-treatable wrought alloys can be strengthened by cold working only and are usually designated in the 1000, 3000, 4000, or 5000 series. The degree of cold working is termed the aluminum strain hardening or temper, denoted by an "H" followed by a number.

Certain alloying elements, such as copper, magnesium, zinc, and silicon, show increasing solid solubility in aluminum with increasing temperatures. Many aluminum alloys containing these elements can be heat treated to enhance the initial strength. These alloys are heat treated by first raising the alloy to an elevated temperature below the melting point, called the solutioning temperature, which puts the soluble element or elements into solid solution. This is followed by quickly cooling the material, usually by quenching in water, to retain the elements in solid solution at room temperature. At this stage the freshly quenched alloy structure is very workable. By storing such material at below-freezing temperatures, this workable alloy structure can be retained until the fabrication is ready to form the alloy into the desired final shape. Such alloys after quenching are not stable at room or elevated temperatures because precipitation of the constituents from the supersaturated solution takes place. After a period of several days at room temperature or hours at an elevated temperature, the alloy is considerably stronger. This process is called age hardening or precipitation hardening. The degree of hardening or temper produced by heat treatment is denoted by a "T" followed by a number.

(2) Identification of Aluminum Alloys. Aluminum alloys are identified by specific numbers. Alloys belong to certain series depending on the particular alloying elements. The 1000 series consists of the high purity aluminums containing at least 99 percent aluminum. These alloys are characterized by having high thermal and electrical conductivity, excellent corrosion resistance, excellent workability, but low strength. These alloys can only be hardened by cold working. Major impurities are iron and silicon.

Copper is the major alloying element of the 2000 series. These alloys are solution heat treated to obtain optimum properties. Some alloys of this series are aged at slightly elevated temperatures, a process called artificial aging, to obtain increased yield strength. The corrosion resistance of the alloys in the 2000 series is less than most of the other aluminum alloys. Sheet forms of these alloys are often clad with high purity alloy or a magnesium-silicon alloy of the 6000 series which provides galvanic protection to the core material and therefore increases resistance to corrosion. Manganese is the principal alloying element of the 3000 series alloys. Alloys of this group generally cannot be heat treated, but can be hardened by cold working.

Silicon is the major alloying element of the 4000 series, which in sufficient quantities, lowers the melting point without producing brittleness. Aluminum-silicon alloys are used in welding and brazing wire where the lower melting point is beneficial in joining other aluminum alloys. Although most alloys of this group are nonheat-treatable, during welding of heat-treatable alloys, some elements from the parent material may be picked up by the weld metal providing joints that may be strengthened by heat treatment.

The 5000 series of alloys contains magnesium. Although these alloys are nonheat-treatable, the addition of magnesium produces alloys having moderate to high strength, good welding characteristics, and good corrosion resistance to marine atmospheres. These alloys are subject to stress corrosion cracking if employed in the cold-worked condition in services where the temperature exceeds about 65° Celsius (150° Fahrenheit).

The 6000 series of aluminum alloys contains both silicon and magnesium in approximate equal proportions which combine during melting to form magnesium silicide. Alloys of this series are heat-treatable, and possess good formability and corrosion resistance with medium strength. One of the most versatile heat-treatable alloys is the major alloy of this series, 6061.

Zinc is the major alloying element of the 7000 series, and when coupled with a smaller percentage of magnesium results in heat-treatable alloys of very high strength. Small amounts of other elements such as chromium and copper also may be added. Alloys in this series are used in air-frame structures and for high-stressed parts. Among the high strength aluminum alloys, 7075 can be heat treated to 565 megapascals (82 000 pounds per square inch) tensile strength, and 496 megapascals (72 000 pounds per square inch) yield strength.

The complete designation of aluminum alloys includes the temper designation, separated from the alloy designation by a hyphen, as for example 7061-T6. The basic temper designations are as follows:

F as fabricated - no special control is exercised over thermal conditions or strain hardening.

O annealed - heat treated to obtain lowest strength temper and improved ductility.

H strain hardened (wrought products only).

W solution heat treated (applies only to alloys hardenable by thermal heat treatment) - an unstable temper, describing the condition between solution treatment before aging. Subfreezing is sometimes used to preserve this temper against natural aging.

T thermally treated to produce stable tempers other than F, O, or H.

Numbers following the basic temper designations further describe the specific combination of operations affecting the temper and in turn the mechanical properties. Specifications, such as those of the American Society for Testing and Materials (ASTM), fully define the alloy composition, mechanical properties and other requirements for applicable aluminum materials. Alloys 5083, 5086, 5052, and 6061 are the most popular aluminum alloys for applications exposed to marine atmospheres. The 5000 series of alloys are the most corrosion resistant, but the 1000, 3000, and 6000 alloys have been used in marine atmospheres. These aluminums may be also employed in the splash zone, but are not recommended for continuous immersion in seawater.

c. Copper and Copper Alloys. Copper has several unique properties. Properties such as high thermal and electrical conductivity, excellent corrosion resistance in normal atmospheric conditions, good workability, and availability at reasonable cost make copper a first choice for conductors in electrical equipment. Copper can be alloyed to produce alloys having improved strength, corrosion resistance, creep resistance, and machinability.

The U.S. copper industry through the Copper Development Association used to designate alloys by a three-digit identification system. This recently has been expanded to five digits, following a prefix letter C, and made part of the Unified Numbering System for Metals and Alloys (UNS) developed and managed jointly by ASTM and the Society of Automotive Engineers (SAE). In the UNS system, numbers C10000 through C79999 denote wrought alloys. Cast alloys are numbered from C80000 through C99990. Within these two catagories, the alloy compositions are grouped into families of coppers and copper alloys as presented in Table 27.

Copper like other metals that have a recrystallization temperature, or softening temperature, above room temperature can be hardened by cold working. If the cold-worked metal is exposed to temperatures above a certain critical temperature determined by the amount of cold work received and the composition of the metal or alloy, the microstructure changes from marked distortion to a recrystallized structure. Yield strength, tensile strength, and hardness are reduced to the same as the alloy had before cold working. The recrystallization temperature or softening temperature of copper can be raised by adding sufficient quantities of silver, phosphorous, cadmium, tin, arsenic, or antimony. Such coppers are often alloyed to raise the softening temperature to above that at which soldering is to be performed so that the benefits of increased strength due to cold working can be retained in the final product.

Copper alloys that are precipitation hardenable contain beryllium, chromium, zirconium, or nickel in combination with silicon or phosphorus. Alpha aluminum bronze containing cobalt or nickel is also precipitation hardenable. During hardening, these alloys are heated to an elevated temperature, held a sufficient time for solid solutioning to occur, then rapidly cooled to room temperature, followed by aging at an intermediate temperature. Beryllium copper (C17200) in the solution annealed and aged condition has a usual tensile strength of 1 210 megapascals (175 000 pounds per square inch).

Copper and copper alloys have useful corrosion resistance for marine application. Most corrosion resistant to seawater are aluminum brass, classified as a miscellaneous copper-zinc alloy; inhibited admiralty, a tin brass containing elements which inhibit the loss of zinc; and the copper-nickel alloys. These alloys form films of corrosion products that provide protection even in flowing seawater. The limiting velocity where these films are lost depends on the alloy. Copper and copper alloys are attacked by ammonium hydroxide due to the formation of a soluable component. Copper alloys containing more than 15 percent zinc are susceptible to stress corrosion cracking due to ammonium ion, and also dezincification, i.e., the loss of zinc due to selective corrosion. Stress corrosion cracking occurs at areas of high stress that can become more anodic than the surrounding metal. Corrosion occurs at the interfaces of the metal crystals that are perpendicular to the stress, weakening the bonding between crystals until cracking occurs. Dezincification occurs in waters having a high oxygen and carbon dioxide content.

d. Other Alloys. Nickel aluminum bronzes and-two phase aluminum bronzes are transformation hardenable. These alloys are heat treated by heating to an elevated temperature to form a single phase solid solution,

Table 27. Classification of Coppers and Copper Alloys

Copper No.	Classification
C10000 through C15999	Coppers (Cu ≥ 99.3 pct)
C16000 through C19999	High copper alloys (96 pct < Cu < 99.3 pct)
C20000 through C29999	Copper-zinc-alloys (brasses)
C30000 through C39999	Copper-zinc-lead alloys (leaded brasses)
C40000 through C49999	Copper-zinc-tin-alloys (tin brasses)
C50000 through C52999	Copper-tin alloys (phosphor bronzes)
C53000 through C59999	Copper-tin-lead alloys (leaded phosphor bronzes)
C60000 through C64699	Copper-aluminum alloys (aluminum bronzes)
C64700 through C66399	Copper-silicon alloys (Silicon bronzes)
C66400 through C69999	Miscellaneous copper-zinc alloys
C70000 through C72999	Copper-nickel alloys
C73000 through C79999	Copper-nickel-zinc alloys (nickel-silver)
C80000 through C81199	Coppers (Cu ≥ 99.3 pct), cast
C81200 through C82999	High copper alloys (96 pct < Cu < 99.3 pct), cast
C83000 through C83999	Copper-tin-zinc and copper-tin-zinc-lead alloys (red brasses and leaded red brasses), cast
C84000 through C84999	Semired brasses and leaded semired brasses, cast
C85000 through C85999	Yellow brasses and leaded yellow brasses, cast
C86000 through C86999	Manganese and leaded manganese bronze alloys, cast
C87000 through C87999	Copper-zinc-silicon alloys (silicon bronzes and silicon brasses), cast
C90000 through C91999	Copper-tin alloys (tin bronzes), cast
C92000 through C94699	Copper-tin-lead alloys (leaded tin bronzes and high-leaded tin bronzes), cast
C94700 through C94999	Copper-tin-nickel alloys (nickel-tin bronzes)
C95000 through C95999	Copper-aluminum-iron and copper-aluminum-iron-nickel alloys (aluminum bronzes), cast
C96000 through C96999	Copper-nickel-iron alloys (copper-nickel), cast
C97000 through C97999	Copper-nickel-zinc alloys (nickel-silver), cast
C98000 through C98999	Copper-lead alloys (leaded copper), cast
C99000 through C99990	Special alloys, cast

held a sufficient time for solutioning to occur, then cooled rapidly to produce a metastable, ordered, close-packed-hexagonal beta phase structure, much like the transformation structure that is formed during the quenching of high carbon steel from a temperature above the austenitizing temperature. This structure is very hard but too brittle for most engineering purposes and must be tempered by heating to an intermediate temperature, typically 595° to 650° Celsius, and holding for a sufficient time to reprecipitate fine acicular alpha phase particles in the tempered beta phase structure. Tempering stabilizes the structure and restores ductility and toughness.

e. Galvanic Coupling. When two dissimilar metals are in electrical contact with each other and immersed in an electrolyte, a potential is established and electrical current may flow. This potential is related to the relative tendency of each of the metals to go into solution. The more active metal acts as the anode and corrodes at a faster rate than it would by itself. The more noble (stable) metal acts as the cathode and is protected. This phenomenon is known as galvanic corrosion. The two dissimilar metals electrically connected are called a galvanic couple. Table 28 presents a galvanic series for flowing seawater at ambient temperature for several metals and alloys. This galvanic series is based on practical measurements of corrosion potentials at equilibrium in seawater. Galvanic corrosion is most likely to occur if the two metals are widely separated in the series. The rate of corrosion is dependent on current density.

Table 28. Galvanic series in flowing seawater (2.4 to 4.0 m/s) at ambient temperature.

Magnesium
Zinc
Aluminum alloys
Calcium
Carbon steel
Cast iron
Austenitic nickel cast iron
Copper - nickel alloys
Ferritic and mortensitic stainless steel (passive)
Nickel copper alloys, 400, K-500
Austenitic stainless steels (Passive)
Alloy 20
Ni - Cr - Mo alloy C
Titanium
Graphite
Platinum

If two dissimilar metals must be joined, several steps may be taken to minimize galvanic corrosion:

(1) Choose metals close together in the galvanic series to reduce the potential;

(2) avoid unfavorable area effects by keeping the cathodic area small in relation to the anode, thereby reducing current density;

(3) insulate the two metals from each other, making sure contact is not restored in service by grounding or corrosion products bridging the insulator;

(4) use coatings: the anodic material must be completely covered to prevent rapid attack at holidays in the coating; sometimes it is also beneficial to coat the cathodic material to reduce current density; and

(5) place a more anodic third metal in contact with the other two so that this third metal provides sacrificial protection.

2. Joining, Cutting and Repairing Metals.

a. Rivets and Bolts. Riveting, at one time, was the primary means of joining metals together. Today the importance of riveting in construction has lessened because of the developments of welding and high strength bolting. The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code no longer lists riveting as an acceptable method for pressure vessel fabrication, although repairs can be made to riveted vessels in accordance with the code requirements that were used for the vessel construction. Riveted joints have one important advantage over bolted joints. Properly set, rivets do not loosen. In spite of its lack of favor in construction, riveting is an important joining method in manufacturing.

Rivets are made from bar stock by hot or cold forming the head. Round button heads are most common but flattened and countersunk types are also produced. For structural steel fabrication, steel rivets should be specified to ASTM Standard Standard A502, Steel Structural Rivets. This standard lists three grades, all of which are intended to be hot driven. Grade 1 is a carbon steel rivet for general purpose, usually used for joining steel conforming to ASTM Standard A36. Grade 2 is a carbon-maganese steel rivet used for joining high strength carbon and high strength low alloy structural steels. Grade 3 is about the same strength as grade 2 rivet steel, but because copper and chromium are required in the steel composition, grade 3 rivets have enhanced atmospheric corrosion resistance approximately four times that of carbon steel without copper. Grade 3 rivets correspond to steels conforming to ASTM Standard 588, High Strength Low-alloy Structural Steel with 340 megapascals (50 000 pounds per square inch) Minimum Yield Point to 10.2 centimeters (4 inches) Thick. Steel rivets are also listed in ASTM Standard A31, Boiler Rivet Steel and Rivets, for repair of riveted boilers and pressure vessels, and in ASTM A131, Structural Steel for Ships. Rivets meeting the requirements of ASTM A31 or ASTM A131 are not suitable for structural construction unless these rivets have also met requirements of ASTM A502. One important difference in the requirements between these standards is that ASTM A502 requires hardness tests, whereas the other standards specify tensile tests on the rivet steel.

Holes for rivets may be punched or drilled. If punched, it is recommended that the holes also be reamed to remove distorted metal, particularly if the structure may be subjected to vibration. For steel construction, the holes are usually 1.6 millimeters (1/16 inch) in diameter larger than the nominal diameter of the undriven rivet. Flame cutting of holes is not recommended because of the microstructural changes that occur in steel.

Temporary bolts are often inserted in a few holes as an alinement aid and to help draw the structural steel members together. Steel rivets are usually driven hot by heating to 982° Celsius (1 800° Fahrenheit). During driving a second head is formed and the rivet shank may be expanded to fill the hole. As the rivet cools, it shrinks and squeezes the connected pieces together. The magnitude of this clamping force depends on the driving and finishing temperature of the riveting operation, the overall grip length, and the driving pressure. Because these are variables that are difficult to control, no credit may be claimed for clamping force in design calculations.

Riveting is used to advantage in joining aluminum structural alloys that have been heat treated for greater strength. The high heat encountered in welding reduces the strength of heat-treated aluminum. Less skill is required for riveting than for welding. The specification covering wire and rod to be used in aluminum rivet manufacture is ASTM Standard B316-75, Aluminum-alloy Rivet and Cold-Heating Wire and Rods. Of the listed alloys, alloys 1100, 3003, 5005, 5052, 5056, and 6061 are most suitable for joining aluminum alloys in coated structures. The 6061 alloy is the only alloy that can be heat treated to obtain higher strength levels.

Bolts are made from bar stock. High strength steel bolts are made by open-hearth, basic oxygen, or electric furnace process. They are fine-grained and must meet ASTM Standard A588-75. The atmospheric corrosion resistance of this steel is approximately two times that of carbon structural steel with copper. High strength bolts are made using various types of quenching and tempering processes and are used in structural connections where high stress and corrosion resistance are required.

Bolts are used to advantage in structural installation where welding is not practical and where working connections are necessary such as tongue and groove pile connections, bulkhead wales, and tiebacks. It is common practice to oversize bolt requirements in marine exposures as an allowance for excessive metal loss from corrosion.

b. Welding. Welding processes most likely to be used during coastal structure construction include gas welding, arc welding, and thermite welding. Other processes, such as resistance welding, friction welding, and induction welding, are used during fabrication of mechanical and electrical equipment. Each welding process has areas of application where its use is the most economical for the desired level of quality.

Gas welding is classified by the gases used; i.e., air-acetylene, oxy-acetylene, oxy-stabilized methylacetylene-propadine, and oxy-hydrogen. The oxyacetylene flame has the highest temperature, about 3 371° Celsius (6 100° Fahrenheit), that can be obtained with commercially available gases. Because the temperature produced by the oxyacetylene flame is far above the melting point of most metals, rapid localized melting necessary for welding is produced.

Oxyacetylene is suitable for welding carbon and alloy steel, cast iron, copper, nickel, aluminum and zinc alloys. Lower melting temperature alloys, such as aluminum, magnesium, zinc, lead and some precious metals, can be gas welded using hydrogen, methane, or propane fuel gases. Gas welding is not

suitable for joining the refractioning metals such as columbium, tantalium, molybdenum, and tungsten nor reactive metals such as titanium or zirconium.

By varying the relative amounts of fuel gas to oxygen in the gases flowing to the tip of the welding torch, the characteristics of the flame can be altered. When fuel gas and oxygen are supplied in the stoichiometic ratio for complete combustion, a neutral flame is produced. As more oxygen is introduced, an oxidizing flame is produced. Slightly less oxygen than that required for a neutral flame results in a reducing flame. Still less oxygen results in a carburizing or carbon impregnating flame. In any flame, the highest temperature is reached at the tip of the inner cone.

In oxyacetylene welding, an oxidizing flame is never used to weld steel but is used sometimes to weld copper and copper base alloys. The copper oxide slag that forms on top of the weld provides shielding from the weld puddle. Temperatures exceeding 315° Celsius (600° Fahrenheit) can be obtained in oxidizing oxyacetylene flames. The reducing flame is frequently used for welding with low alloy steel rods. Flame temperature at the tip of the inner cone is usually 2 930° to 3 040° Celsius (5 300 to 5 500° Fahrenheit). The carburizing flame has a tendency to soot the cold work but is useful where lower temperatures are required such as for silver brazing, soldering, and in the melting of lead. For most oxyacetylene welding, a neutral flame is used. When welding steel the outer envelope provides protection to the molten weld puddle, and no flux is required.

Fluxes are required when oxyacetylene welding stainless steel, cast iron, and most nonferrous metals. There is no universal flux suitable for all metals. The function of the flux is to clean the metal surfaces to be joined and to provide protection to the weld puddle by lowering the melting point of the metal oxides or dissolving these oxides so they rise to the top of the weld pool forming a protective slag covering. Fluxes are not required for welding lead, zinc, and some precious metals.

c. Underwater Arc Welding. Although many experts consider underwater welding suitable only for emergency ship repairs of a semipermanent nature, satisfactory permanent welds can be accomplished using special techniques. Sometimes underwater welding is the only practical method of making attachments or repairs on such underwater structures as drilling platforms or bulkheads. Three different techniques have been used for performing welding below the waterline. These are wet welding, dry welding, and welding using either a caisson open to the surface attached to the area to be welded, or a special habitat constructed around the area to be welded. Underwater wet arc welding requires the use of divers in full deep-diving suits. The helmets are fitted with supplementary hinged faceplates with appropriate welding glass. It is advisable for the diver's head to be insulated from the helmet by wearing a cap, and by covering metal with insulating tape. Scuba diving is suitable only at shallow depths because it is required that the diver be in voice communication with topside assistant. Topside welding assistants operate the power source at the command of the diver-welder. Electrodes for underwater welding must be waterproofed using proprietary products or coatings of cellulose acetate. Some brands of electrodes are also satisfactory without additional coatings. Because these coatings can be only considered as providing temporary protection, divers should carry only a few electrodes at a time. The Navy recommends 4.75-millimeter (3/16 inch) electrodes of

type E6013 for all positions except where the section size is too thin for this size electrode. Other electrodes, such as waterproofed iron powder electrodes, may be satisfactory. Qualification testing should be performed. Electrodes for underwater welding are designed for straight polarity, i.e., the electrode is negative. If reverse polarity is used underwater, the electrode holder is consumed due to electrolitic action. It is important that the electrode holder be insulated and be designed to permit easy changing of electrodes by the diver.

Power sources for underwater arc welding should be capable of delivering at least 300 amperes of rectified or direct current. Because welding is usually done at considerable distances from the power source, the welding cables should be at least size 2/0. To facilitate maneuverability, the last 3 meters (10 feet) of cable at the electrode holder is usually size 1/0. A safety switch is installed in the circuit that is closed only while the welder is actually welding. For good electrical continuity, the ground cable must be securely attached to the work after first cleaning the contact area. Provided the pieces to be welded fit together properly, 4.75-millimeter fillet welds can develop 44 kilonewtons (10 000 pounds) tensile strength per 25.4 millimeters (1 inch). Using 4.75-millimeter electrodes and the drag technique where the electrode is allowed to consume itself as it is pressed against the work, 4.75-millimeter fillet welds are produced in a single pass. Stringer bead technique should be used if additional weld reinforcement is required. Because visibility is poor under water, multipass welds are difficult to finish after the first bead is laid because the guiding groove is filled. Fillet welds can be made in the horizontal, vertical, and overhead positions.

Bubbles generated during welding interfere with visibility. Welders minimize this problem by welding toward themselves when making horizontal welds and from the top down when making vertical welds.

Underwater welds in mild steel plate develop 80 percent or more of the tensile strength, but only 50 percent of the ductility of similar welds made in air. This substantial decrease in ductility is explained by the hardening resulting from the drastic quenching of the surrounding water. Because it is not possible to preheat weld areas wet by water, to avoid cracking underwater welding should not be attempted on base materials having carbon contents above 0.25 percent or carbon equivalents (percent carbon plus 0.17 percent manganese) above 0.40 percent. The area to be welded must be free from marine growth, paint, mill scale, and rust to assure sound welds. Electric shock is a hazard that must be taken into account by equipment and safety procedures. Another hazard that could be overlooked is the possible explosion resulting from the accummulation of hydrogen and oxygen gas in closed or inadequately exposed compartments or spaces. Bubbles generated during arc welding are about 70 percent hydrogen and are produced by electrolysis of the water. Such accummulations of hydrogen can be ignited by spark or flame.

Underwater work including welding has been accomplished dry in air using a caisson open to the surface. Such a structure must be strongly constructed to stand the pressure of the water, approximately 9.8 kilopascals per meter of depth (62.4 pounds per square foot per foot of depth), depending on salt content and temperature. A caisson has been used to repair a tear 13.7

meters (45 feet) below the surface, in the stainless steel liner of a water-filled storage pool. Habitats have been used to make underwater modifications to a drilling platform in the Gulf of Mexico. Habitats can be constructed to surround the areas to be welded and filled with air so that preheating of the weld areas is possible. Welds produced under these conditions will basically have the same strength and ductility as welds produced under the same condition topside. Habitats used in welding are usually open at the bottom. Because of buoyancy, the habitat must be securely attached and weighted. A constant flow of air through the habitat is necessary to remove the fumes produced by welding, but electrolysis and hydrogen formation is avoided because water is kept away from the arc.

d. Underwater Cutting. Underwater cutting is used in salvage work and wherever cutting below the waterline is required on steel structures such as docks, piers, drilling platforms, and ships. The two most widely used methods are flame cutting and oxygen arc cutting.

The technique used for underwater flame cutting is not too different from flame cutting steel in air. In each method, a fuel gas in a torch is mixed with oxygen and burned to produce a flame that preheats the steel, and a cutting jet is provided to supply oxygen to cut the steel. The underwater cutting torch, however, contains one important difference in construction. The underwater torch supplies its own ambient gas atmosphere, an air bubble around the flame, by means of compressed air that is ejected through a special nozzle surrounding the tip. An adjustable shield on the top of the torch is also usually supplied to help control the formation of the air bubble and to allow the torch to be held at the optimum distance from the work, even under conditions of poor visibility and constraint due to the cumbersome diving suits that must be worn. Slots are cut in the shield to allow gases to escape. The underwater torch is furnished with three hoses, for compressed air, oxygen, and fuel gas.

Underwater flame cutting is most effective in severing a steelplate in the thickness range of 12.7 to 152 millimeters (1/2 to 6 inches). Below 12.7 millimeters, the quenching effect of the water retards the cutting action greatly.

It is important that the air hose never be used for oxygen. Compressed air may contain some oil which can coat the hose causing an explosion when oxygen is introduced. Fuel gases are usually hydrogen or natural gas because these gases can be used at any depth without liquifying. Acetylene is almost never used in underwater cutting because at pressures more than 207 kilopascals (30 pounds per square inch) acetylene becomes unstable and may decompose violently even if no oxygen is present.

A standard welding power source, capable of supplying 300 amperes of direct current straight polarity, is satisfactory for oxygen arc cutting under water. Electrode holders are fully insulated and of a special design so that both oxygen and current can be supplied to the electrode. To reduce resistance losses, cables should be size 2/0, except the last 3 meters (10 feet) at the torch which may be 1/0 for added flexibility. If the power source is more than 120 meters (400 feet) from the work, parallel cables of 1/0 or 2/0 are required. All underwater cable connections should be wrapped with rubber tape. A safety switch must be provided so that the torch is energized only while cutting.

Electrodes for underwater oxygen arc cutting are either tubular carborundum or steel. Steel electrodes are available in 4.75- and 7.93-millimeter (3/16 and 5/16 inch) diameters with a 1.6-millimeter-diameter (1/16 inch) bore. These electrodes are provided with a waterproof coating, which serves as an insulator during cutting.

Cutting underwater requires that positive pressure be maintained by the electrode against the metal being cut; whereas, in air, the electrode is dragged along the intended line of cut. Particular attention must be paid to safety. The power sources must be grounded to the tender and ground cables securely connected to the work. All parts of the power cables and torches must be fully insulated and periodically inspected. An operating disconnecting switch must be part of the cutting electrical circuit. To prevent possible explosions, enclosed spaces must be vented so that gases generated during cutting cannot accummulate.

3. <u>Environmental Considerations</u>.

a. <u>Exposure to Air</u>.

(1) <u>General</u>. In contrast to organic materials, sunlight exposure does not cause deterioration of metals. Under some conditions, however, sunlight can be a contributing factor in the stress corrosion cracking of some stainless steels. Stress corrosion cracking occurs where high stress accelerates corrosion along intercrystalline boundaries, leading to weakening of intercrystalline bonds and eventual cracking. Austenitic stainless steels, such as type 304, 316, 321, 347, and even 216, are susceptible to stress corrosion cracking when exposed simultaneously to heat, stress, chloride ion, and oxygen. Cold-worked materials are most susceptible; however, even annealed austenitic stainless steel contains some residual stresses from fabrication and can crack. Stress corrosion cracking is believed to be time dependent, but the exact threshold conditions for this phenomenon to occur have not been established. Process equipment constructed of austenitic stainless steel and hydrotested with seawater but not properly drained and flushed has been ruined by stress corrosion cracking where the only heat applied was the heat of the sun.

(2) <u>Effect of Severe Temperatures</u>. At one time, harbor facilities were located only in the torrid or temperate zones. Many ships were built of riveted construction. Welded ships were constructed by fitting each plate individually in turn. World War II created a demand for cargo ships that only mass production techniques could meet. These techniques involved constructing large hull sections offsite, then moving them into position for welding together to complete the hull. Because alinement of the sections was not perfect, force was applied to obtain sufficient alinement for welding. Many of these ships broke in two in the North Atlantic. Investigations revealed that brittle failure was the cause of these losses. Today, knowledge of the relationship between notch toughness and brittle failure enables marine structures to be designed to survive the most severe temperatures.

Carbon and most alloy steels suffer a decrease in toughness as temperatures are reduced. When slow rates of loading are applied these materials exhibit increased tensile and yield strength with only a slight loss of elongation and reduction of area at reduced temperatures. When the load is

rapidly applied, as in the Charpy impact test, the amount of energy absorbed during fracture decreases gradually as testing is performed at progressively lower temperatures until, at some temperature, the absorbed energy drops dramatically. This temperature is known as the nil ductility transformation (NDT) temperature, the temperature at which the specimen exhibits little ductility before fracture. The NDT temperature can be defined by Charpy V-notch testing as (1) the temperature at which a certain absorbed energy is attained, (2) the temperature at which 50 percent shear fracture is attained on the broken specimen, or (3) the temperature at which a certain lateral expansion is attained on the specimen opposite the notch. A common value for minimum absorbed energy at the NDT temperature for ordinary constructional steels is 20 newton meters (15 foot-pounds); however, acceptable impact values are often stated in ASTM or other material specifications. Complete procedures for conducting many mechanical tests on metals including impact tests are given in ASTM A370. Figure 48 presents a representative plot of absorbed energy versus temperature for Charpy V-notch tests on a typical carbon steel.

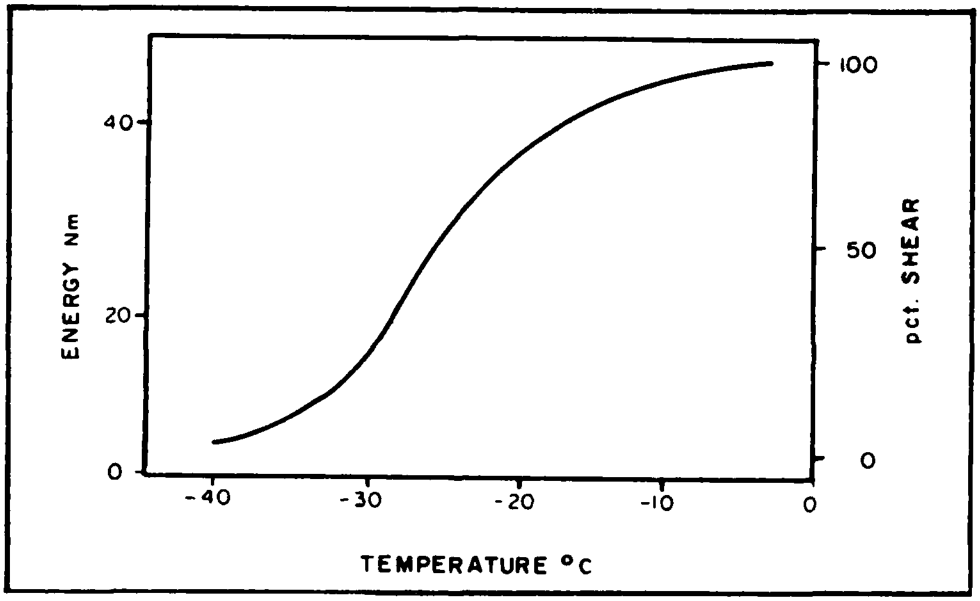


Figure 48. Plot of Charpy V-notch test on a low carbon steel.

Values obtained from Charpy V-notch testing cannot be directly used in engineering calculations for design. Notch toughness values become significant only when correlated with a particular type of structure in a particular service. These values are useful to compare different materials. The NDT temperature determined by Charpy V-notch testing has correlated rather well with temperatures at which service failures have occurred for components of the same steel.

Factors affecting the notch toughness of a metal are as follows:

(a) Chemical composition,

(b) gas content,

(c) microstructure (e.g., size, shape and orientation of grains, and grain boundaries of a structure),

(d) grain size,

(e) section size, (physical cross-section dimensions),

(f) hot and cold working temperature,

(g) method of fabrication, and

(h) specimen orientation in relation to working direction.

Figure 49 presents representative plots of Charpy V-notch absorbed energy curves for several materials used in construction. Fully killed carbon steel made using a fine grain melt practice in the normalized heat treatment has the best notch toughness at lower temperatures of the carbon steels. If sulfide shape control is used during processing, improved notch toughness can be obtained in the transverse (across grain) and through (with grain) section directions. Austenitic stainless steel, type 304, and 9-percent nickel are candidate materials for handling liquefied gases. Notice that gray cast iron exhibits little notch toughness at any temperature shown.

(3) Wind Erosion. Wind erosion does not have a severe effect on metals. Wind-driven sand, however, can destory paint and therefore increase the formation of rusting on steel structures. Appearance is the property most often affected.

b. Exposure to Flora. The major effect of flora on metals is a slight increase in corrosion rate where the plants, by their root system, may transport additional moisture to the metal surface. In some soils, aerobic bacteria are present that oxidize sulfur which is either present in the soil or is obtained from decaying organic matter. By oxidation of sulfur, a strong solution of sulphuric acid is formed that reacts with any basic material present. The presence of either anaerobic or aerobic bacteria can cause soils to be corrosive to metals even though a usual mineral analysis of the soil and water does not reveal that a corrosive condition exists.

c. Exposure to Burrowing Animals. Most metals have high hardness which prevents burrowing animals from penetrating. Animals have damaged the insulation covering of some buried electrical cables, which resulted in failure of the cables.

d. Exposure to Freshwater.

(1) General. Exposed surfaces of metals are subject to some degree of corrosion from water. The corrosiveness of water is basically dependent on three factors; acidity, oxygen content, and electrical conductivity. Many rivers are polluted by industrial wastes or runoff from mines causing the water to become acid. Such water may be more corrosive to carbon steel than seawater would be. Rainwater becomes slightly acid as it falls to earth due to saturation with carbon dioxide. As the rain contacts the earth it becomes altered by reaction with minerals and soil. Depending on the acidity and

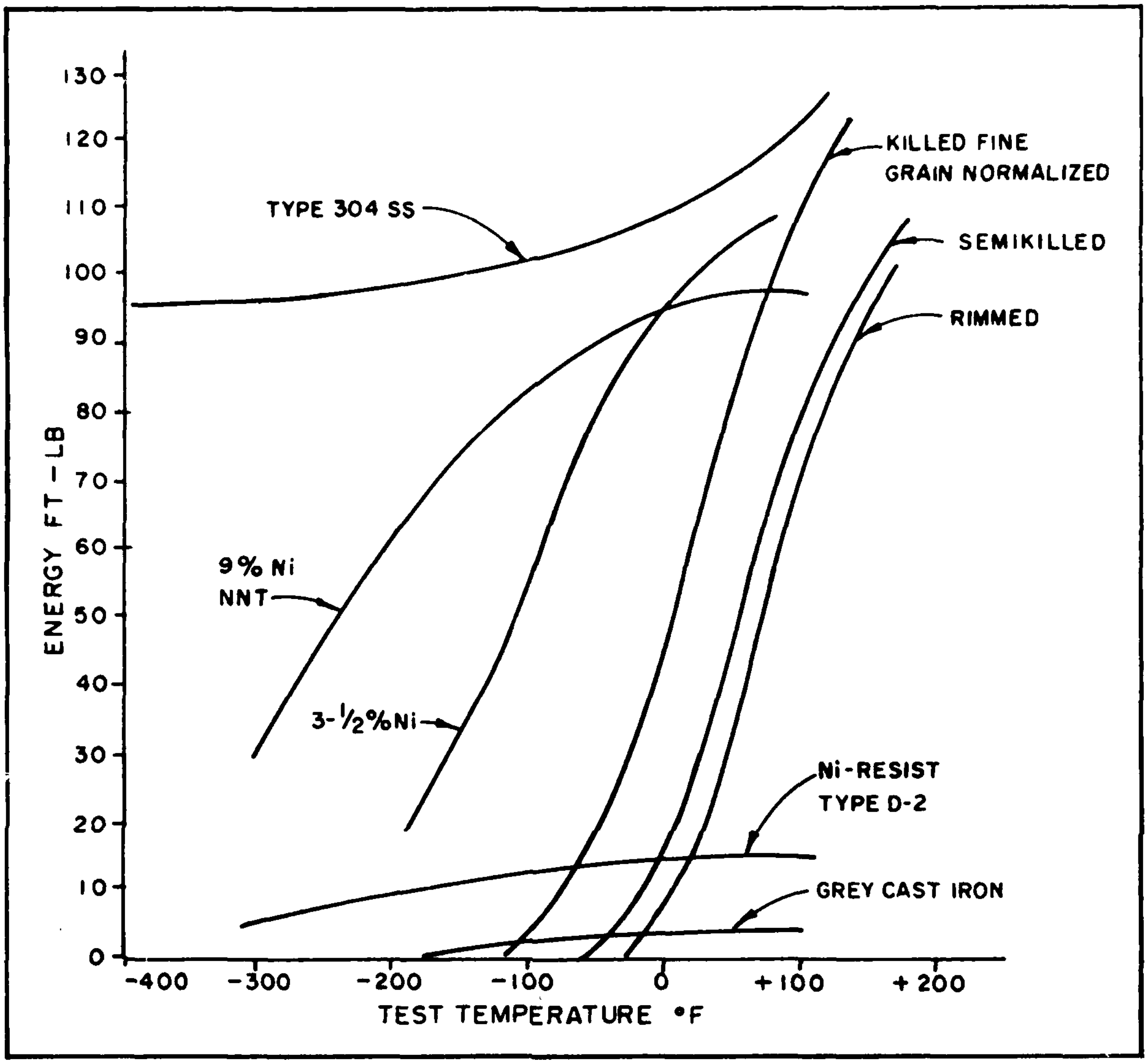


Figure 49. Representative Charpy V-notch absorbed energy curves for several materials. (Data compiled from International Nickel Company, 1976, and American Society for Metals, 1978).

mineral composition, stream water may be less corrosive to carbon steel than rainwater.

(2) Water Penetration Effects. Metals are impervious to water penetration.

(3) Freezing and Thawing. The volume expansion of ice in fine-grained soils, such as very fine sand, silt, or clay, may produce lateral thrusts to sheet-pile structures. Placement of free-draining coarse granular soil above the frostline behind sheet-pile walls should eliminate the possibility of lateral thrust from ice or frozen ground. Steel sheet piling can

yield laterally to relieve any thrust load due to ice. Plugged and broken waterlines caused by ice are inconveniences that require cooperation between design and construction personnel, and between operations and maintenance personnel to eliminate this problem. Heat tracing and insulation are solutions to this problem, but other methods may be more practical such as pumping out fire hydrants, and closing doors to heated loading docks.

e. Exposure to Saltwater.

(1) Corrosion Effects - General. Corrosion rates of metals in seawater are higher than in pure water because ions of halogen compounds, such as sodium chloride, have the power to cause localized breakdown of oxide films that are responsible for passivity and corrosion resistance. Halogen ions can form soluble acidic corrosion products, such as ferric chloride, which interfere with the restoration of passivity to steel leading to localized corrosion in the form of pitting. Tests have shown that corrosion rates for carbon steel in the atmosphere at the shoreline are 10 times the rates shown by plates 460 meters (500 yards) from the shoreline.

It has been shown that the rate of corrosion of steel in seawater and in freshwater is governed to a large extent by the oxygen content. Carbon steel, in contact with freshwater saturated with oxygen at ambient temperature, usually exhibits a corrosion rate of 220 micrometers (9 mils) per year general corrosion plus an additional 220 micrometers per year of pitting. When freshwater is oxygen-free, the corrosion rate for carbon steel is usually only 25 micrometers (1 mil) per year or less, provided no corrosive pollutants are present.

(2) Variable Oxygen Content. The pattern of corrosion found on steel pilings in the atmosphere, the splash zone, the tidal zone, submerged in clean seawater, and in the mud zone varies considerably. A principal variable related to position is the oxygen content. The high corrosion rate in the splash zone is attributed to the constant wetting of the steel by highly aerated seawater. In the tidal zone, differential aeration produces a protective cell effect, resulting in a considerably lower corrosion rate. At deeper positions, less oxygen is present and the corrosion rate for steel drops to rates usually in the range of 76 to 152 micrometers (3 to 6 mils) per year. Carbon steel in seawater that has been treated to remove dissolved oxygen and marine bacteria exhibits an even lower corrosion rate under low velocities.

Austenitic stainless steel and aluminum alloys exhibit satisfactory corrosion resistance in the splash zone, because the high oxygen content helps keep passivating films intact. Aluminum has better corrosion resistance in the splash zone than at greater depths where less oxygen is present. The high corrosion rates on carbon steel piling in the splash zone may also be attributed to the severe electrochemical corrosion cells set up in the pile. Piles made from high-copper-bearing, high-strength, low-alloy steel conforming to ASTM Standard A690 have two to three times the resistance to seawater corrosion in the splash zone of ordinary carbon steel, although such steels exhibit no better corrosion resistance at greater depths.

(3) Effects of Polluted Seawater. Polluted waters often contain hydrogen sulfide which causes severe effects in metals sensitive to the

effects of sulfides. Hardened steel, or welds not stress relieved in medium carbon steel, may crack due to stress corrosion. Hydrogen sulfide presence can lead to corrosion of the vapor side of copper alloy heat exchangers. Small amounts of ammonia may also be present in polluted seawater, causing aggressive attack and stress corrosion cracking of copper-zinc alloys. The copper-nickel alloys are preferred when ammonia pollution is expected and the 90-10 copper nickel alloy (UNS No. C70600) has demonstrated satisfactory performance in many applications where sulfide pollution has been present.

f. Effects of Marine Organisms. Biofouling and biological fouling are common terms that refer to the settlement and growth of living organisms on materials exposed to the marine environment. Some metals, such as titanium and the nickel-chromium-high molybdenum alloys, are completely corrosion resistant under fouling. Copper base alloys exhibit varying degrees of resistance to biofouling. Other materials such as aluminum, carbon steel, and stainless steel both foul and suffer increased corrosion due to biofouling. On structures such as wharves and breakwaters, biofouling may not be of as much importance. However, biofouling causes increased wave action loadings on such structures. Increased flow blockage and decreased heat transfer efficiency are other problems encountered as result of marine biofouling on metal structures in marine service.

Biofouling resistance is highest for copper and the 90-10 copper nickel alloy. Brass and bronze have good resistance but 70-30 copper nickel alloy, aluminum bronze, zinc (galvanizing), and Monel alloy 400 have only fair biofouling resistance. The high resistance to biofouling of many of the copper-base materials have been attributed by some researchers to the inhospitable nature of the green cupric hydroxychloride corrosion product that forms on these materials. This film is itself loosely attached so that any marine organisms that do attach to this film are soon removed. Monel, carbon steel, aluminum, and stainless steel exhibit poor corrosion resistance under biofouling. Carbon steel suffers general corrosion, whereas Monel, aluminum, and stainless steel exhibit pitting and crevice corrosion. Crevice corrosion is caused by differential oxygen cells produced when oxygen is prevented from reaching the metal surface under barnacles.

Corrosion rates on carbon steel may be reduced a little when biofouling is present due to reduced velocity of water at the metal surface; however, corrosion rates remain relatively high. Biofouling will periodically slough off when the corrosion product breaks off. The high general corrosion rate of carbon steel in seawater is attributed to marine organisms known as anaerobic bacteria. Principal groups are the sulphate-reducing and the iron-consuming bacteria. The sulphate-reducing bacteria require oxygen, which is derived from the reduction of compounds such as sulphates, sulphites, thiosulphates, or organic substances rather than dissolved oxygen. These bacteria liberate hydrogen sulphite which attacks iron severely, removing hydrogen from the cathodic areas of the steel with the formation of iron sulphide. The iron-consuming bacteria do not actually consume iron as food but do require iron in solution for growth.

Biofouling has been controlled by using copper base alloys, antifouling coatings, mechanical cleaning of the surface, or environmental controls. Environmental control measures include increased flow velocity, elevated

temperature, and chlorination. When employing such control measures, the corrosion performance of the base metals must be considered.

In addition to biofouling, there are several organisms (such as limnoria, teredo, and termites) common in the marine environment that cause deterioration of structures through boring. Because metal structures are impenetrable these organisms do not cause deterioration usually found on marine pilings constructed of wood.

g. Wave and Current Effects. Fouling diminishes as water velocities in contact with a structure reach the 1- to 2-meter-per-minute (3 to 6 foot) range. Pitting of the more noble materials slows down and may even cease. As velocities continue to increase, stainless steel and nickel base materials remain passive and inert but corrosion barriers are stripped away from carbon steel and copper alloys. Although wave or current velocity are seldom too high to allow the use of carbon steel, velocity is a factor to consider in the design of equipment such as piping and pumps.

h. Abrasion. Abrasion to metal structures is caused by the movement of the elements in the coastal zone and their ability to transport particles with force against all structures. Significant particle transport is caused by wind and water. Structures in windswept beaches and shores are subject to severe abrasion from the wind-driven sand with substantial force and can result in significant metal wear in the case of steel or other metal structures. For steel pile structures, abrasion to piles at the mud line increases the metal loss far in excess of loss from corrosion. For some structures, usually on land or for structural elements located above the waterline in the ocean, added abrasion resistance can be provided by additional protection in the form of concrete, wood, or hard-surfaced alloys Most hard-surfaced metals require special heat treating and the addition of small amounts of other elements such as manganese.

The latest improvement in steel piling was the development of mariner steel for seawater exposure. Mariner steel was developed primarily to improve the corrosion resistance of steel in seawater by alloying about 0.5 percent each of copper and nickel in addition to about 0.1 percent of phosphorous (ASTM Standard Specification A 690-77). While mariner steel has a somewhat improved strength, its hardness is little different than that of normal steel piling and abrasion resistance is also little different. Although cathodically protected steel structures in seawater usually take on a calcareous coating (chemicals deposited from the seawater) this coating is too soft to offer any resistance to abrasion.

i. Seismic Effects. Metals are well suited for marine construction in areas of seismic activity. They possess high tensile strength, good ductility, and, when properly specified, good toughness. In addition, metals can consistently meet specified minimum seismic requirements. Steel, the most economical of the metals for construction of harbor facilities, is available in several shapes. The inherent high-bending strength of steel H-piles permits the development of required resistance to lateral forces, when used in foundation designs where resistance to seismic forces is required. The ability of metals to be loaded in shear, compression or tension within calculated limits facilitates the design of earthquake-proof structures.

j. Fire. Metals in the shapes and sizes used in construction will not burn in a fire; however, these do have reduced strength as temperatures rise. Carbon steel is affected above 340° Celsius (650° Fahrenheit). At 480° Celsius (900° Fahrenheit), carbon steel has only about half the strength that it does at room temperature. During a fire, structures of all steel construction have collapsed. Structures are protected from fire loss by the installation of sprinkler systems, which spray water on the building and roof supports to keep them cool and by the covering of steel beams and supports with concrete to provide insulation. Metals that have experienced a fire should be tested for suitability before being reused because strength and toughness may be reduced. Heat treatment may be required to restore properties.

k. Human Activity. Accidents and theft are two elements of human activity that the designer must consider. Piers and wharves are constructed with fender systems to minimize damage from impact by ships. When accidents do cause damage, metal structures may be repairable by welding.

Legs on drilling platforms are often sheathed with copper nickel alloys in the splash zone areas to minimize corrosion. Attempts to use similar methods in harbors have not been completely successful because the sheathings have been stolen for their metal value as scrap.

4. Uses of Structural and Sheet Metal.

a. General.

(1) Steel. Various parts of coastal structures are made of steel. Steel H-piles or pipe piles are used to support foundations. Steel H-piles are used in preference to steel pipe piles because they are more easily driven in soils containing hard strata or obstructions such as boulders. Steel H-piles are easily spliced by welding, allowing driving to deep rock strata if necessary. Steel H-piles are also frequently used to support fender systems immediately in front of the wharves. Steel bolts are used to attach rubber bumpers to the fender system that prevents damage to the structure by absorbing the ship impact loads. Cast-steel bollards and mooring posts are used to take up ships' lines. Steel is an ideal material for breasting and mooring dolphins because steel can be easily jointed, has high tensile strength, good ductility, and good toughness. Structural steel shapes are used for framing of structures. Even the fences around coastal installations are most often chain-link steel fences.

Large quantities of steel are used in components that appear to be all concrete. Concrete piles, beams, structure foundations, walls, roadways, and pads all will contain steel reinforcing bar, wire or wire fabric. Materials for concrete reinforcement are covered in Section V, Portland Cement Concrete.

(2) Aluminum. Many alloys of aluminum possess high corrosion resistance to marine atmospheres as well as good strength-to-weight ratios. These properties make aluminum an economic choice for many applications in coastal structures, particularly where freedom from maintenance is desired.

In buildings, door and window frames are usually 6063 aluminum, roofing and siding, alclad 3004 aluminum. Tread plate, such as used for decking and catwalks, is 6061 aluminum heat treated to T4, T42, or T6 temper. Aluminum alloys are also used for architectural trim, hardware, and gutters and downspouts. Insulation is even faced with aluminum foil to reflect heat, making the insulation more effective.

Electrical wire and bus bars are either copper or 1350 aluminum. Because the conductivity of 1350 aluminum is approximately one half that of copper, the cross section of the aluminum conductor must be approximately twice that of the copper for equivalent current capacity. The specific gravity of aluminum is so much less than that of copper that equivalent conductors of 1350 aluminum weigh only half those of copper, making the choice one of economics. Lamp poles and standards are made from 6063 aluminum. Even the lamp bases may be 3004 or 5050 aluminum.

Tanks and equipment for liquid natural gas facilities must be constructed of materials having high notch toughness. Aluminum alloys 5083 and 5456 have been specified for liquid natural gas storage tanks and vaporizers because these alloys have good corrosion resistance to marine atmospheres and high notch toughness. In accordance with ASTM A370, aluminum alloys do not require Charpy impact testing because aluminum alloys do not become brittle at cryogenic temperatures.

(3) Copper. Electrical conductors such as wire and bus bars are the largest applications of copper. Copper is also used for pipe and sheathing. Coppers are used in many hidden applications in supporting equipment at coastal structures. Such uses include radiators in air conditioners and powered equipment, springs and contacts in communication and control systems, and even tools of beryllium copper for use in areas where sparks must be prevented to avoid fires and explosions. Copper alloys are used in equipment such as heat exchangers, pumps, valves, and hardware for sluice gates and traveling water screens.

(4) Nickel. Nickel base alloys have good corrosion resistance to seawater and generally high resistance to cavitation damage. Most resistant are nickel-chromium-molybdenum columbium alloy 625 (Inconel 625, produced by Huntington Alloys, Huntington, West Virginia) and nickel-molybdenum-chromium alloy C (Hastelloy C, produced by Stellite Division, Cabot Corporation, Kokomo, Indiana). These two alloys are used for springs, cable connectors, bellows-type expansion joints, rupture disks, and pump seal rings in coastal facilities.

Nickel-copper alloy 400 (Monel 400, produced by Huntington Alloys) is the lowest cost nickel base alloy for marine service. This alloy is used for valve and pump trim, fasteners, heat exchangers, and piping.

(5) Titanium. The major uses of titanium in coastal structures are steam condensers employing seawater cooling, ball valves, and desalination equipment. Titanium will tolerate polluted seawater under conditions where other materials fail. As a result, many coastal powerplants are installing steam condensers using titanium tubes.

b. Sheet-Pile Structures.

(1) Design. Bulkheads in waterfront facilities are subjected to lateral pressure resulting from earth movement and the unbalanced hydrostatic and seepage forces acting on opposite sides of the wall. A higher water level may exist in the backfill behind the wall than in front of it as a result of a receding tide, receding high water, or a heavy rainstorm. Other lateral loads that may be encountered are ice thrust, wave forces, ship impact, mooring pull, and earthquake forces. Because of its material strength sheet pile is often used in marine construction for bulkheads. The designer, after evaluating the lateral pressure and forces, must determine the required depth of piling penetration, the maximum bending moments in the piling, and the maximum bending stresses in the wall. An appropriate sheet-pile section must be selected, taking into account yield strength and moment of inertia of the selected section. Some typical steel sheet-pile profiles are shown in Figure 50. A choice may be made between a cantilevered or anchored wall.

Anchored sheet-pile walls can be designed for greater height than is possible with the cantilever-type design with a similar sheet-pile section. For heights to about 11 meters (35 feet) (depending on soil conditions), sufficient support can be obtained from anchor tie rods near the top of the wall and the lateral support of the embedded part of the wall. For greater heights, higher yield strength steel or multiple tie rods at lower levels are required. Anchorage systems in use include deadman anchors, H-pile anchors, and sheet-pile anchors. Sketches of the systems are shown in Figure 51. Regardless which anchorage system is used, the anchor must be located outside the potential active fracture zone behind the sheet-pile wall. Passive resistance of the anchor is not possible if the ground is unstable.

A complete sheet-pile wall system may consist of the wall, wale, tie rods, and the anchor. The wale is a flexible member attached to the wall which distributes the horizontal reactive force from the anchor tie rods to the wall section. Locating the wale on the outside of the wall where the piling will bear against the wale in compression is preferred for engineering purposes. However, wales are sometimes bolted onto the inside face to provide a clear outside face.

Wales are often constructed of steel structural channels conforming to ASTM Standard A36 mounted with their webs back to back, and separated by enough space to clear the end of tie rod between them. When the wales are located on the inside face, each sheet-pile section is bolted to the wale. Standard wale designs for wales located on both outside and inside faces are shown in Figure 52.

Tie rods are usually round steel bars, conforming to ASTM Standard A36, that have been upset and threaded at each end so as to maintain cross-sectional area in the threaded part. Usually a turnbuckle is used between two tie-rod sections to allow removal of slack. Sagging of the tie rods may occur because of soil settlement around them which drags them downward, causing increased tension in the rods. Two methods of avoiding this condition are: (1) use light vertical piles at 6- to 9-meter (20 to 30 foot) intervals to support the rods, or (2) encasing the rods in large conduits.

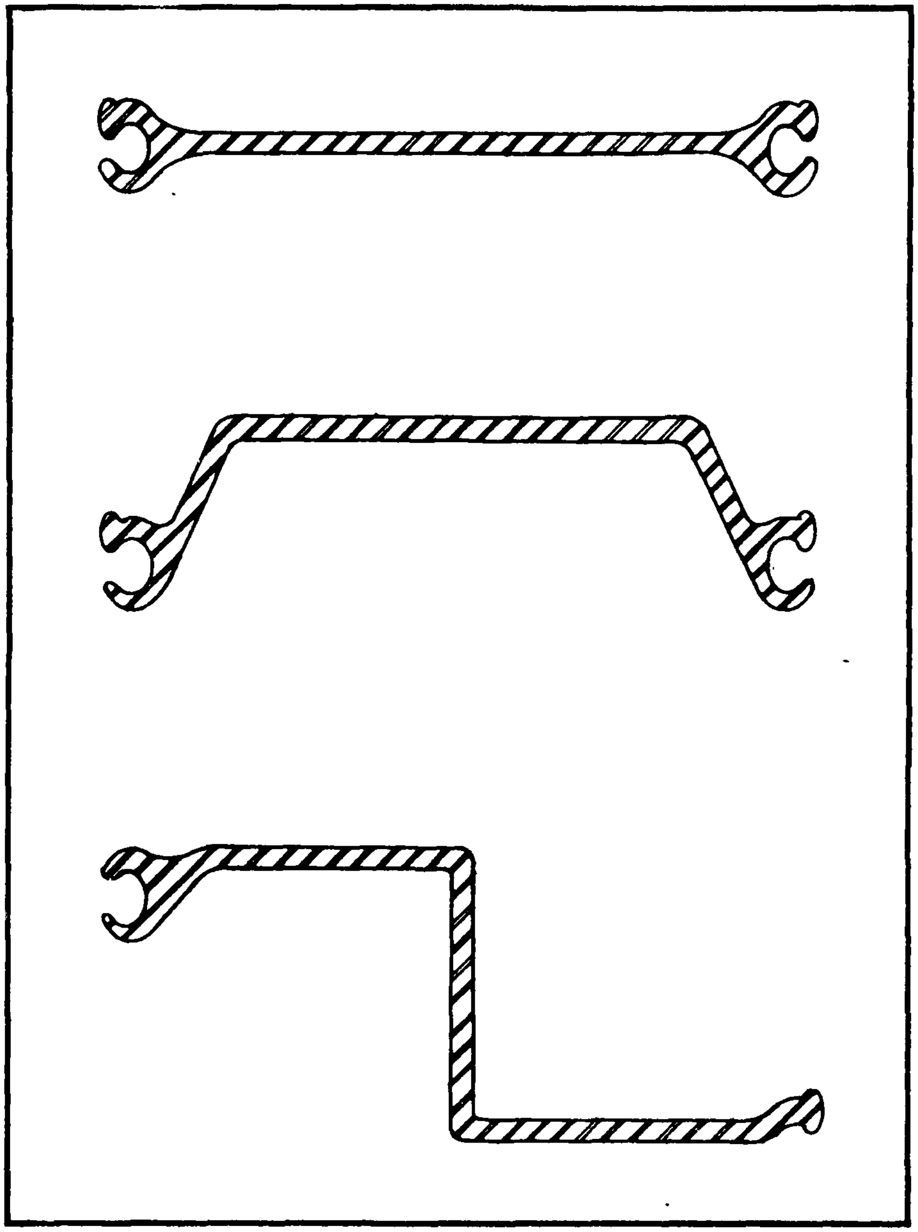


Figure 50. Typical steel sheet-pile profiles -- top view, straight; middle view, arch, bottom view, angle.

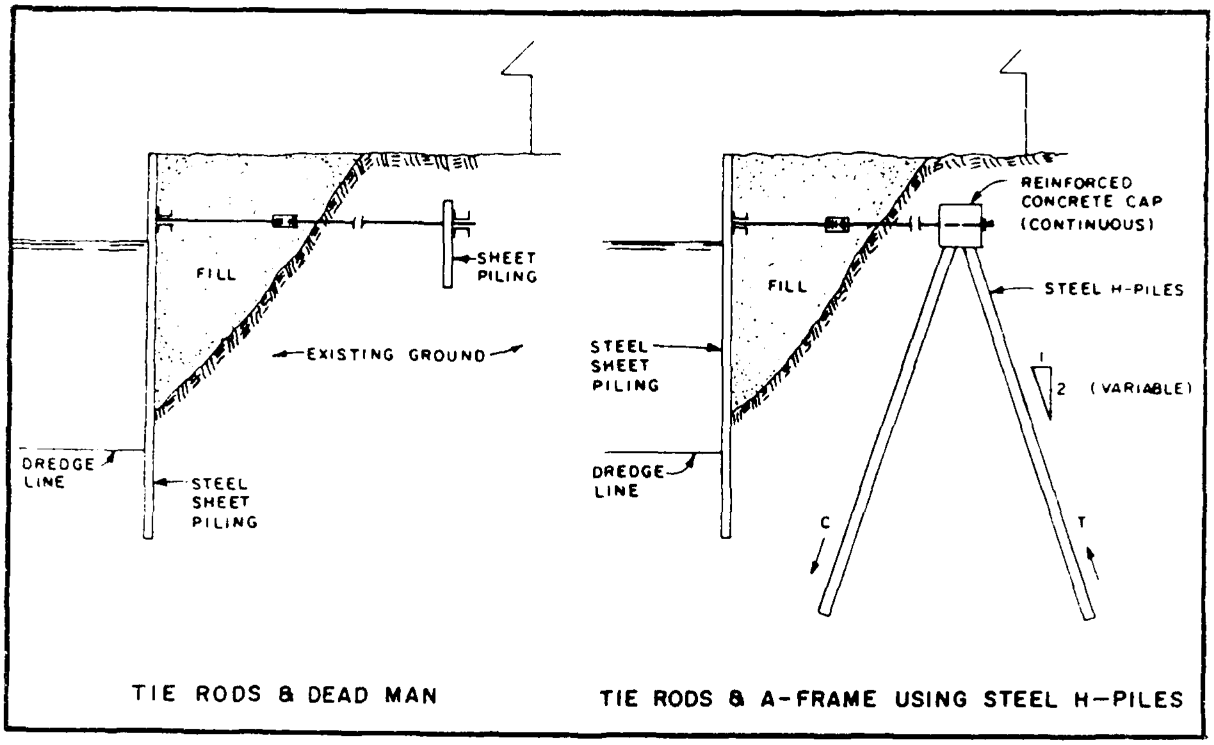


Figure 51. Typical-steel pile anchorage systems.

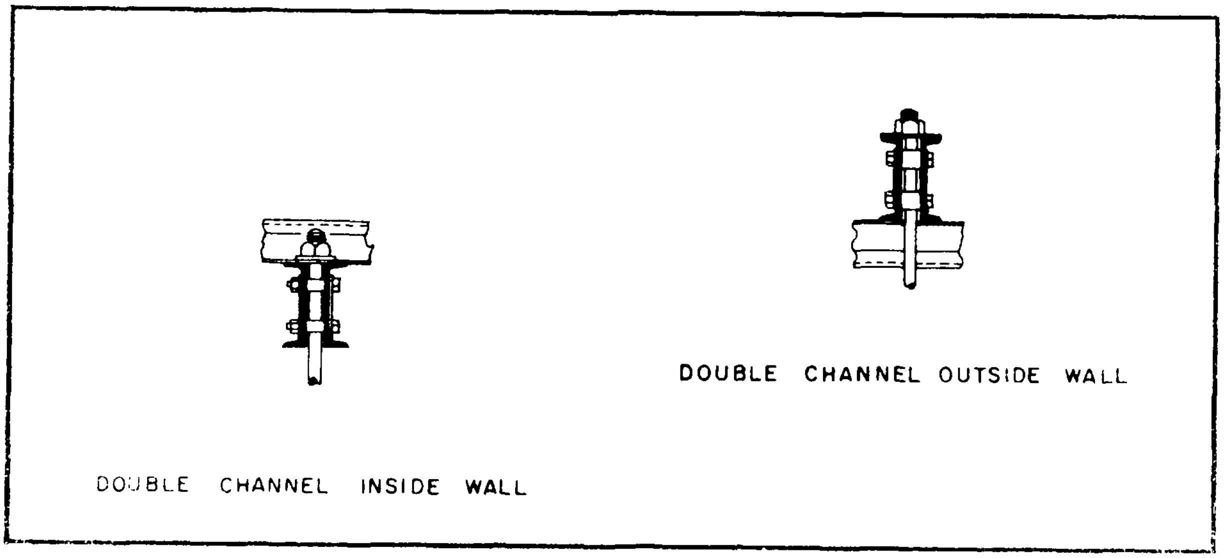


Figure 52. Standard wale designs.

Tie rods are subject to corrosion and must, therefore, be adequately coated and wrapped.

(2) Construction. Steam hammers are commonly employed for pile driving in the United States. During driving, the steam hammer, consisting of a housing and the moving part called the ram rests on top of the pile. A single acting steam hammer is a freely falling ram with steam pressure acting on a piston to raise the ram prior to fall. In a double acting hammer, steam is not only used to lift the ram but also to help drive the ram downward. Double acting hammers are able to deliver blows faster than single acting hammers of the same energy output because double acting hammers use a shorter stroke and higher ram acceleration. Both drop hammers and diesel hammers are also available. A drop hammer consists of a heavy weight or ram that is allowed to fall by gravity on top of the pile. Fall height must be controlled to avoid damage to pile heads by excessive impact from rams moving with high velocity.

Excessive impact or improper cushioning during pile driving may result in mashed pile heads. Vertical misalinement of the pile as a result of obstructions encountered below the ground surface or of poor pile-driving conditions may cause failure of pile interlocks. If excessive misalinement occurs, sheet piles can become over stressed resulting in bulkhead failure.

The method used for the construction of steel breakwaters depends on the soil conditions and the height of the waves. If the waves are below 10 feet, and the bottom is soft to a great depth, steel sheet pile topped with concrete and supported with batter piles may be used.

Bulkheads for small-boat harbors have been constructed using sheet piling of aluminum alloy 5052-H141. Coping was of 6063-T6, tie rods and stiffener bar beams of 6061-T6. Deadman anchors were constructed of 5052-H141 alloy. Aluminum sheet pile is available in 3.6-meter (12 foot) lengths which limit application to shallow facilities.

c. Gabions. Gabions, compartmented rectangular containers made of galvanized steel hexagonal wire mesh and filled with small stones, have been used to reinforce the shoulder of seawalls constructed of rock. They have also been used to construct jetties as well as revetments and seawalls to control shoreline erosion. Gabion mattresses can also be used as foundations or filter layers under rubble-mound structures and caisson structures. For seawater use, gabions of galvanized wire should be coated with plastic to reduce corrosion. The Alaska District limits use of gabions in the wave zone where ice occurs due to bursting of the gabions by the ice. Also, if the gabions are not rigidly filled, the rockfilling can move and abrade the wire.

VIII. WOOD

1. General.

Wood is widely used in the coastal zone because it is strong, resilient, and easily installed with common tools and equipment. It is also a common material available nearly everwhere at a reasonable cost. When properly treated, it is very durable. Its ability to absorb energy (resiliency) is a feature that makes it especially desirable for uses such as fender piles.

The main problem when using wood in the coastal zone is that it is an organic material that is the natural food supply and habitat for fungi, bacteria, insects and marine organisms. The first three occur on land and are more active in the high moisture conditions at the coast. Wood treatments to prevent attack by natural enemies are very effective in combating damage from these sources.

2. Physical Properties of Wood.

a. Physical Structure of Wood. Wood is a cellular organic material made up principally of cellulose, which comprises the structural units, and lignin, which cements the structural units together. It also contains certain extractives and ash-forming minerals. Wood cells are hollow and vary from about 1 000 to 8 000 micrometers (40 to 330 mils) in length, and from 10 to 80 micrometers (0.4 to 3.3 mils) in diameter. Most cells are elongated and are oriented vertically in the growing tree, but some, called rays, are oriented horizontally and extend from the bark toward the center, or pith, of the tree.

(1) Hardwoods and Softwoods. Species of trees are divided into two classes: hardwoods, which have broad leaves; and softwoods or conifers, which have needlelike or scalelike leaves. Hardwoods shed their leaves at the end of each growing season, but most softwoods are evergreens. The terms "hardwood" and "softwood" are often misleading because they do not directly indicate the hardness or softness of wood. In fact, there are hardwoods which are softer than certain softwoods.

(2) Heartwood and Sapwood. Several distinct zones are distinguishable in the cross section of a log: the bark; a light-colored zone called sapwood; an inner zone, generally of darker color, called heartwood; and, at the center, the pith (Fig. 53). A tree increases in diameter by adding new layers of cells from the pith outward. For a time, this new layer contains living cells which produce sap and store food, but eventually, as the tree increases in diameter, cells toward the center become inactive and serve only as support for the tree. The inactive inner layer is the heartwood; the outer layer containing living cells is the sapwood. There is no consistent difference between the weight and strength properties of heartwood and sapwood. Heartwood, however, is more resistant to decay fungi than is sapwood, although there is a great range in the durability of heartwood from various species.

(3) Annual Rings. In climates where temperature limits the growing season of a tree, each annual increment of growth usually is

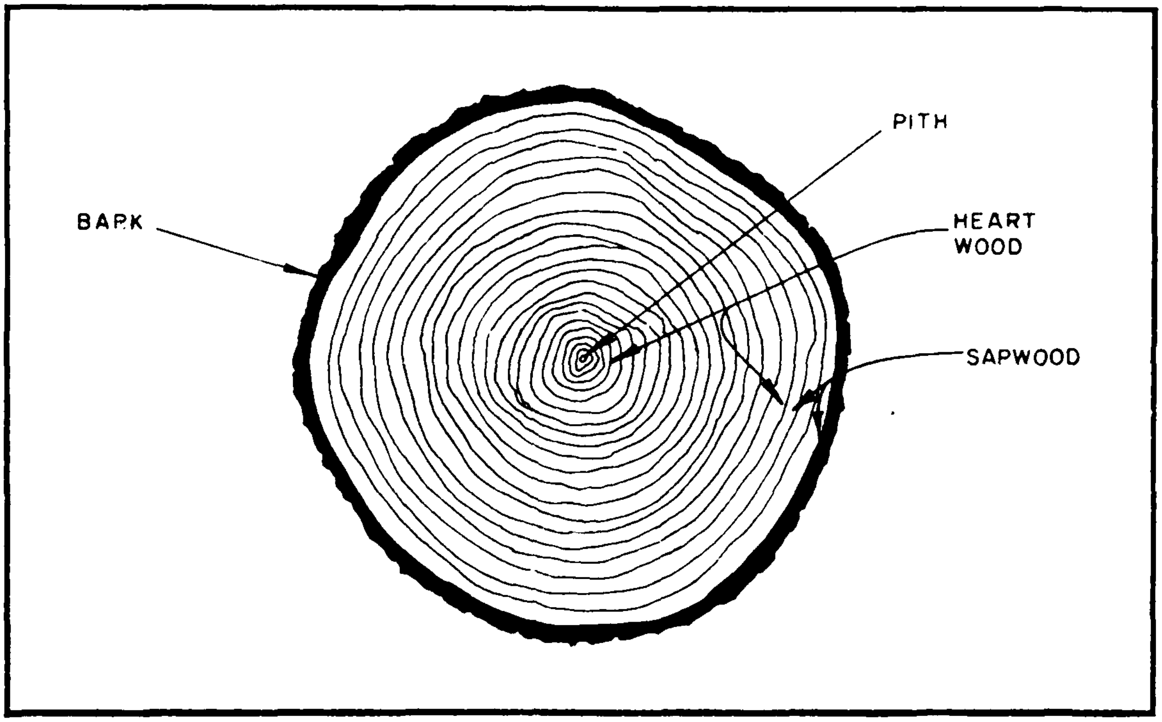


Figure 53. Typical cross section of a log.

readily distinguishable. Such an increment is known as an annual growth ring or annual ring, and consists of an earlywood and a latewood band.

(4) Earlywood (Springwood) and Latewood (Summerwood). In many woods, large thin-walled cells are formed in the spring when growth is greatest, whereas smaller, thicker walled cells are formed later in the year. The areas of fast growth are called earlywood, and the areas of slower growth, latewood. In annual rings, the inner, lighter colored area is the earlywood, and the outer, darker layer is the latewood. Latewood contains more solid wood substance than does earlywood and, therefore, is denser and stronger. The proportion of width of latewood to width of annual ring is sometimes used as one of the visual measures of the quality and strength of wood.

(5) Grain and Texture. The terms "grain" and "texture" are used in many ways to describe the characteristics of wood and, in fact, do not have a definite meaning. Grain often refers to the width of the annual rings, as in "close-grained" or "coarse-grained." Sometimes it indicates whether the fibers are parallel to or at an angle with the sides of the pieces, as in "straight-grained" or "cross-grained." Texture usually refers to the fineness of wood structure rather than to the annual rings. When these terms are used in connection with wood, the meaning intended should be defined.

b. Moisture Content of Wood. Wood may contain moisture as "free water" in the cell cavities and as "absorbed water" in the capillaries of the cell walls. When green wood begins to lose moisture in the seasoning process, the

cell walls remain saturated until the free water has been evaporated. The point at which evaporation of free water is complete and cell walls begin to lose their moisture is called the fiber saturation point (fsp). This point occurs between 25 and 30 percent moisture for most species.

Moisture in wood is expressed as a percentage of the ovendry weight and is determined most accurately by weighing a representative sample, drying it at slightly more than 100^{o} Celsius (212^{o} Fahrenheit), until no further loss of weight takes place, reweighing, and then dividing the difference between the original and final weights by the final (ovendry) weight. Electric moisture meters offer a simpler though less exact method of determining moisture content. With slight seasonal variations, wood in use over a period of time attains an equilibrium moisture content (emc) corresponding to the humidity and temperature of the surrounding atmosphere. When exposed to similar atmospheric conditions, different woods will have the same moisture content regardless of their density.

Moisture content has an important effect upon susceptibility to decay. Most decay fungi require a moisture content above fiber saturation point to develop. In addition, a favorable temperature, an adequate supply of air, and a source of food are essential. Wood that is continuously water-soaked (as when submerged) or continuously dry (with a moisture content of 20 percent or less) will not decay. Moisture content variations above the fiber saturation point have no effect upon the volume or strength of wood. As wood dries below the fiber saturation point and begins to lose moisture from the cell walls, shrinkage begins and strength increases.

c. Directional Properties. Wood is not isotropic because of the orientation of its cells and the manner in which it increases in diameter. It has different mechanical properties with respect to its three principal axes of symmetry: longitudinal (parallel to grain), radial (perpendicular to grain), and tangential (perpendicular to grain) (see Fig. 54). Strength and elastic properties corresponding to these three axes may be used in design. The difference between properties in the radial and tangential directions is seldom of practical importance in most structural designs; for structural purposes it is sufficient to differentiate only between properties parallel and perpendicular to the grain.

d. Specific Gravity. Solid wood substance is heavier than water, its specific gravity being about 1.5 regardless of the species of wood. Despite this fact, dry wood of most species floats in water because a part of its volume is occupied by air-filled cell cavities. Variation among species in the size of cells and in the thickness of cell walls affects the amount of solid wood substance present and hence, the specific gravity. Thus, specific gravity of wood is a measure of its solid wood substance and an index of its strength properties. Specific gravity values, however, may be somewhat affected by gums, resins, and extractives which contribute little to strength. The relationship of specific gravity to wood strength is recommended in the practice of assigning higher basic stress values to lumber designated as "dense."

e. Dimensional Stability.

(1) Effect of Temperature. Wood, like most other solids, expands on heating and contracts on cooling. In most structural designs, the

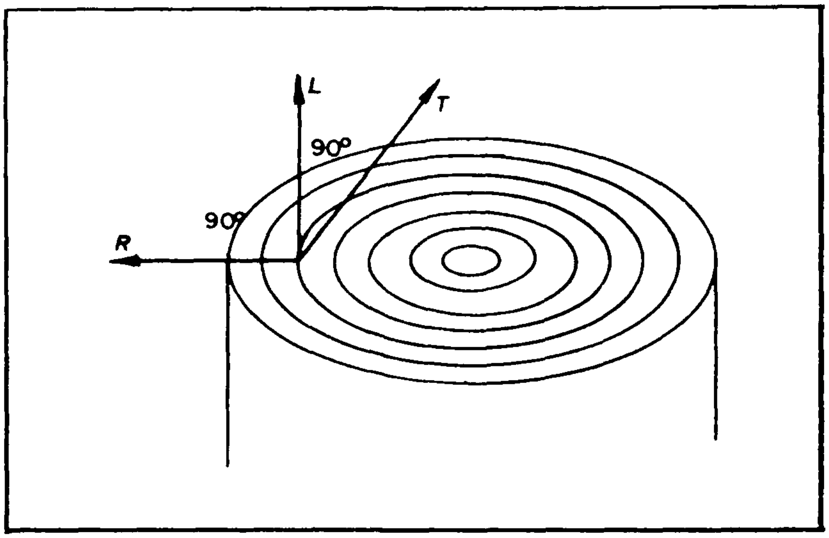


Figure 54. The principal axes of wood: L, longitudinal; R, radial; T, tangential (American Institute Timber Construction, 1974).

increase of wood in length due to a rise in temperature is negligible, and, as a result, the secondary stresses due to temperature changes may, in most cases, be neglected. This increase in length is important only in certain structures that are subjected to considerable temperature changes, or in members with very long spans.

The increase in length per unit of length for a rise in temperature of 1° is designated the coefficient of linear thermal expansion. It differs in the three structural directions of wood. Radially and tangentially (perpendicular to grain), the coefficient of linear thermal expansion varies directly with the specific gravity of the species. It is in the range of 45 x 10^{-6} meters per meter per $^{\circ}$ Celsius (25 x 10^{-6} feet per foot per $^{\circ}$ Fahrenheit) times specific gravity for a dense hardwood such as sugar maple to 81 x 10^{-6} meters per meter per $^{\circ}$ Celsius (45 x 10^{-6} feet per foot per $^{\circ}$ Fahrenheit) times specific gravity for softwoods such as Douglas fir, Sitka spruce, redwood, and white fir. Radial or tangential dimensional changes for common sizes of wood structural members are relatively small. Longitudinally (parallel to grain), the coefficient is independent of specific gravity and varies from 3.08 x 10^{-6} meters per meter per $^{\circ}$ Celsius (1.7 x 10^{-6} feet per foot per $^{\circ}$ Fahrenheit) to 4.5 x 10^{-6} meters per meter per $^{\circ}$ Celsius (2.5 x 10^{-6} feet per foot per $^{\circ}$ Fahrenheit) for different species. This is from one-tenth to one-third of the values for other common structural materials and glass. For this reason, consideration must be given to the different thermal expansion coefficients of various materials used in conjunction with wood. The average coefficient of linear thermal expansion for plywood is 6.12 x 10^{-6} meters per meter per $^{\circ}$ Cels... (3.4 x 10^{-6} feet per foot per $^{\circ}$ Fahrenheit). The coefficient of thermal expansion for thickness is essentially the same as for solid lumber.

(2) Effect of Moisture Content. Between zero moisture content and the fiber saturation point, wood shrinks as it loses moisture and swells as

it absorbs moisture. Above the fiber saturation point there is no dimensional change with variation in moisture content. The amount of shrinkage and swelling differs in the tangential, radial, and longitudinal dimensions of the piece. Engineering design should consider shrinkage and swelling in the detailing and use of lumber.

Shrinkage occurs when the moisture content is reduced to a value below the fiber saturation point (for purposes of dimensional change, commonly assumed to be 30 percent of the moisture content at the fiber saturation point) and is proportional to the amount of moisture lost below this point. Swelling occurs when the moisture content is increased until the fiber saturation point is reached, then, the increase ceases. For each 1 percent decrease in moisture content below the fiber saturation point, wood shrinks about one-thirtieth of the total possible shrinkage, and, for each 1 percent increase in moisture content, the piece swells about one-thirtieth of the total possible swelling. The total swelling is equal numerically to the total shrinkage. Shrinking and swelling are expressed as percentages based on the green wood dimensions. Wood shrinks most in a direction tangent to the annual growth rings, and somewhat less in the radial direction, or across these rings. In general, shrinkage is greater in heavier pieces than in lighter pieces of the same species, and greater in hardwoods than in softwoods.

As a piece of green or wet wood dries, the outer parts are reduced to a moisture content below the fiber saturation point much sooner than are the inner parts. Thus the whole piece may show some shrinkage before the average moisture content reaches the fiber saturation point. Neither the initial nor the final moisture content (M_i or M_f) can be greater than 30 percent when calculating shrinkage because that is the moisture content at which, when drying, wood starts to shrink or at which, when absorbing moisture, it reaches its maximum dimension. Values for longitudinal shrinkage with a change in moisture content are ordinarily negligible. The total longitudinal shrinkage of normal species from fiber saturation to ovendry condition usually ranges from 0.1 to 0.3 percent of the green wood dimension. Abnormal longitudinal shrinkage may occur in compression wood, wood with steep slope of grain, and exceptionally lightweight wood of any species.

The cross-laminated construction of plywood gives it relatively good dimensional stability in its plane. The average coefficient of hydroscopic expansion (or contraction) is about 0.000 2 meter per meter (0.000 2 foot per foot) of length or width for each 10 percent change in relative humidity, or 0.2 percent ovendry to complete saturation.

3. Mechanical Properties of Wood.

a. Wood as Structural Material.

Wood is not an isotropic material because strength properties differ along its different axes. It is strongest when loaded in induce stress parallel to grain, either in tension or compression. However, this condition is not always possible and loading perpendicular to grain may be accomplished in a satisfactory manner.

The anisotropic nature of wood may be confusing to the designer during his first experience with its use, but as he gets to know the material he finds that engineering design with wood can be interesting as well as productive in the way of lower construction costs. The discussion which follows provides a brief description of the various mechanical properties of structural wood as they affect engineering design.

(1) Tension Parallel to Grain. A force generating tension parallel to grain, as shown in Figure 55, creates a tendency to elongate the wood fibers and to cause them to slip by each other. Resistance to tension applied strictly parallel to grain is the highest strength property of wood. This resistance, however, is substantially reduced when the force is applied at an angle to the grain or when the cross section of the piece is reduced by knots or holes.

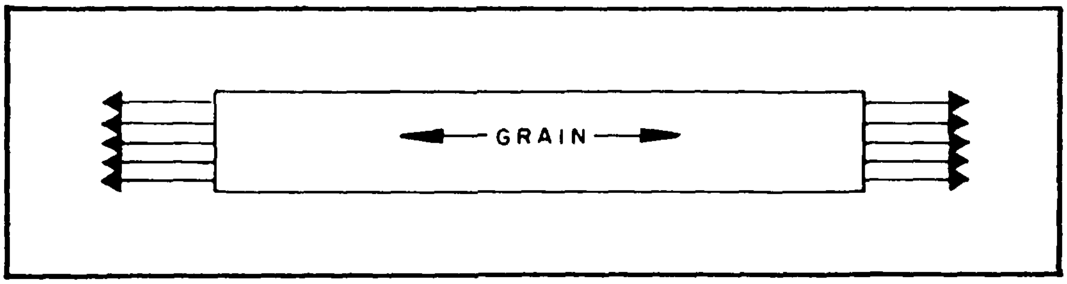


Figure 55. Tension parallel to grain.

(2) Tension Perpendicular to Grain. A force generating tension perpendicular to grain tends to separate the wood fibers along the grain. This is the direction in which wood has the least strength, and because it is not good practice to apply loading to induce tension across grain, design values are not provided for this strength property, except for special applications.

(3) Compression Parallel to Grain. A force generating compression parallel to grain, as shown in Figure 56, creates a tendency to compress the wood fibers in the lengthwise position. As with tension, resistance to compression parallel to grain is affected by the angle of load to grain and by the presence of knots or holes.

(4) Compression Perpendicular to Grain. A force applied perpendicular to grain, such as the bearing under the ends of a beam as shown in Figure 57, tends to compress the wood at its surface. While the wood becomes more dense as it is compressed, this action causes slight displacement of the supported member. Thus, limits are placed on loading in bearing perpendicular to grain.

(5) Shear Parallel to Grain. A force applied in the manner illustrated in Figure 58 causes one section of the piece to shear or slide along the other section in a direction parallel to grain. In a loaded beam where the induced stress on the one side is compression and on the other side is tension, as illustrated in Figure 58, shearing stress is created

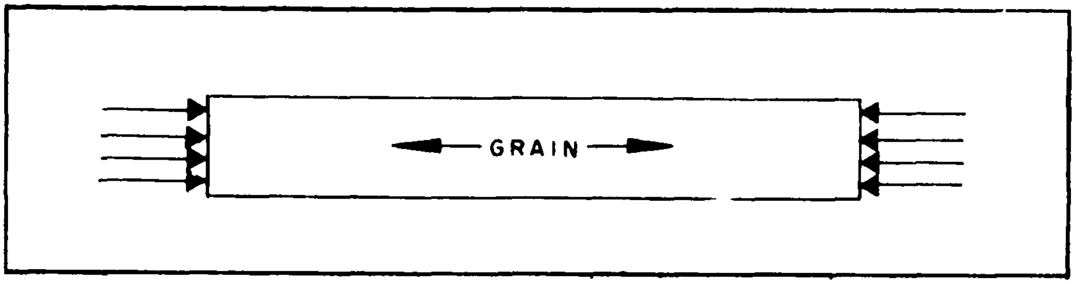


Figure 56. Compression parallel to grain.

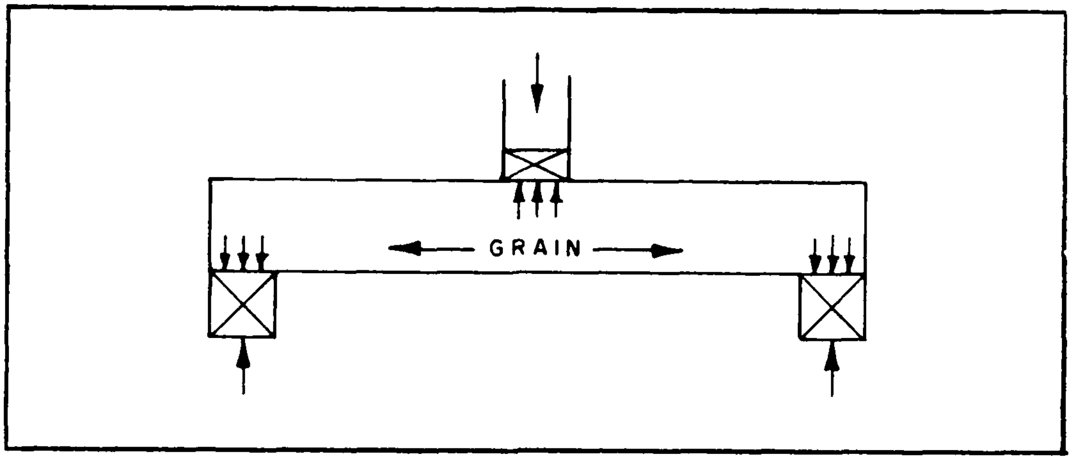


Figure 57. Compression perpendicular to grain.

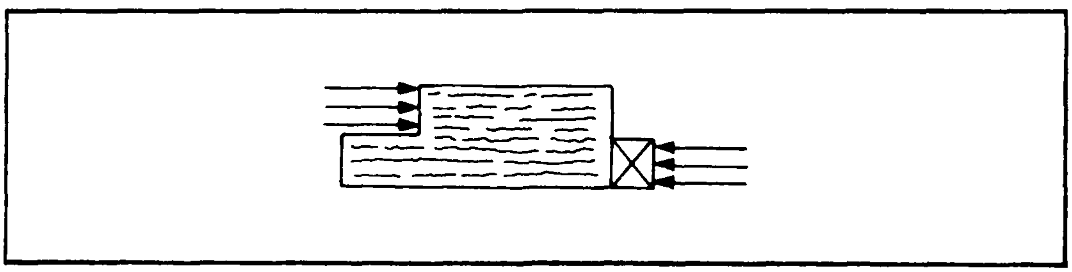


Figure 58. Shear parallel to grain.

parallel to grain. The largest shear stress parallel to grain usually occurs along the neutral axis on the plane at which the induced stress changes from compression to tension and generally increases to the maximum at the supports or end of the beam. Shakes, checks, and splits, which may occur during the drying of lumber, have the effect of reducing the area in the plane of shear resistance. Consequently, laboratory test values for shear strength parallel to grain are substantially reduced for design purposes in order to accommodate the probability of the occurrence of shakes, checks and splits after drying.

(6) Shear Perpendicular to Grain. Shear perpendicular to grain is not a design factor in solid wood because effective control is applied through limits on design stresses in shear parallel to grain and compression or bearing perpendicular to grain.

(7) Fiber Stress in Bending. A force or set of forces applied perpendicular to a beam, as shown in Figure 59, creates compression in the fibers on the side to which the force is applied and it also creates tension in the fibers on the opposite side. Thus, there is a tendency to compress the fibers on the compression side and to elongate the fibers on the tension side. As the stress is distributed from the extreme fibers or outside faces toward the center or neutral axis of the piece it is reduced in intensity. Thus, deviations in slope of grain and the presence of knots or holes in these outside faces tend to reduce the resistance in the extreme fibers and the bending strength of the beam.

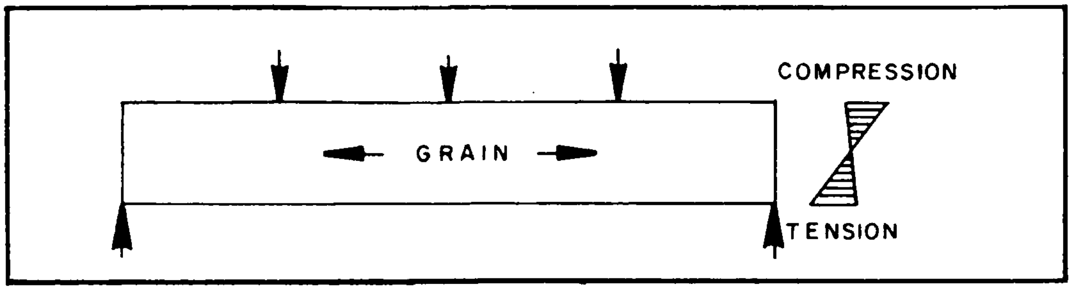


Figure 59. Fiber stress in bending.

(8) Proportional Limit, Static Bending. The proportional limit occurs at the point where the induced strain or deformation ceases to be proportional to the stress or applied load, as determined by the standard test method. Stress at proportional limit is computed by the standard method. All conventional methods of structural design for wood are within the proportional or elastic limit.

(9) Modulus of Rupture, Static Bending. The modulus of rupture is computed from the ultimate load or the point at which the piece breaks under the standard bending test method. Loading by test beyond the proportional limit shows an increasing rate of deformation, without a specific yield point, until ultimate load is reached.

(10) Modulus of Elasticity, Static Bending. The modulus of elasticity is a measure of stiffness and is computed on the basis of the load and deformation within the proportional limit.

b. Design Values For Structural Lumber.

(1) General. Design values are assigned to lumber in a scientific manner to provide material of predictable strength properties to meet the requirements of engineering design. Because of the varying nature of the different species of trees, there is a wide range of stress values from which the designer can make his selection. However, to avoid delay during

construction, it is advisable to determine which species and grades are available locally before design values are selected.

(2) Classification of Structural Lumber. Because the effects of knots, slope of grain, checks, and shakes on the strength of lumber vary with the loading to which the piece is subjected, structural lumber is often classified according to its size and use. The three major classifications are as follows:

(a) Dimension lumber--pieces of rectangular or square cross section, 2 to 4 inches thick and 2 inches or more wide (nominal dimensions) graded primarily for strength in bending edgewise or flatwise but also used where tensile or compressive strength is important; dimension lumber may be further classified as joists and planks, for material 5 inches or more in nominal width, and as light framing or structural light framing for material 2 to 4 inches wide;

(b) beams and stringers--pieces of rectangular cross section, 5 to 8 inches (nominal dimensions) and larger, graded for strength in bending when loaded on the narrow face; and

(c) posts and timbers--pieces of square or nearly square cross section, at least 5 by 5 inches (nominal dimensions) and graded primarily for use as posts or columns but adapted to miscellaneous uses in which bending strength is not especially important.

(3) Characteristics Affecting Strength. Aside from the natural properties of the species, the major characteristics affecting the strength of a piece of lumber are the sizes of knots or holes and their locations, the sizes of checks or shakes and splits and their locations, the amount of wane or absence of wood, slope of grain, degree of density or rings per inch, and the condition of seasoning. All these characteristics are taken into consideration in the stress grading of a piece of lumber. These conditions are illustrated in Figure 60.

(4) ASTM Standards. There are two ASTM standards which serve as principal references in the assignment of working stresses of lumber. One standard is ASTM D2555, "Methods for Establishing Clear Wood Strength Values," which sets forth procedures for establishing strength values for clear wood of different species in the unseasoned condition and unadjusted for end use. Such procedures may be applied to a single species or to a group of species where growth and marketing conditions justify such grouping. The other standard is ASTM D245, "Methods for Establishing Structural Grades for Visually Graded Lumber," which sets forth reduction factors to be applied to the clear wood values and provides procedures for determining strength ratios, based on knots and other characteristics, which, when applied to the adjusted clear wood values, results in working stresses for the various commercial grades of any species. This standard also provides adjustments for degree of density and for condition of seasoning.

(5) Lumber Grading Rules. Lumber grading rules are, in effect, specifications of quality. In the rules the maximum knots, slope of grain

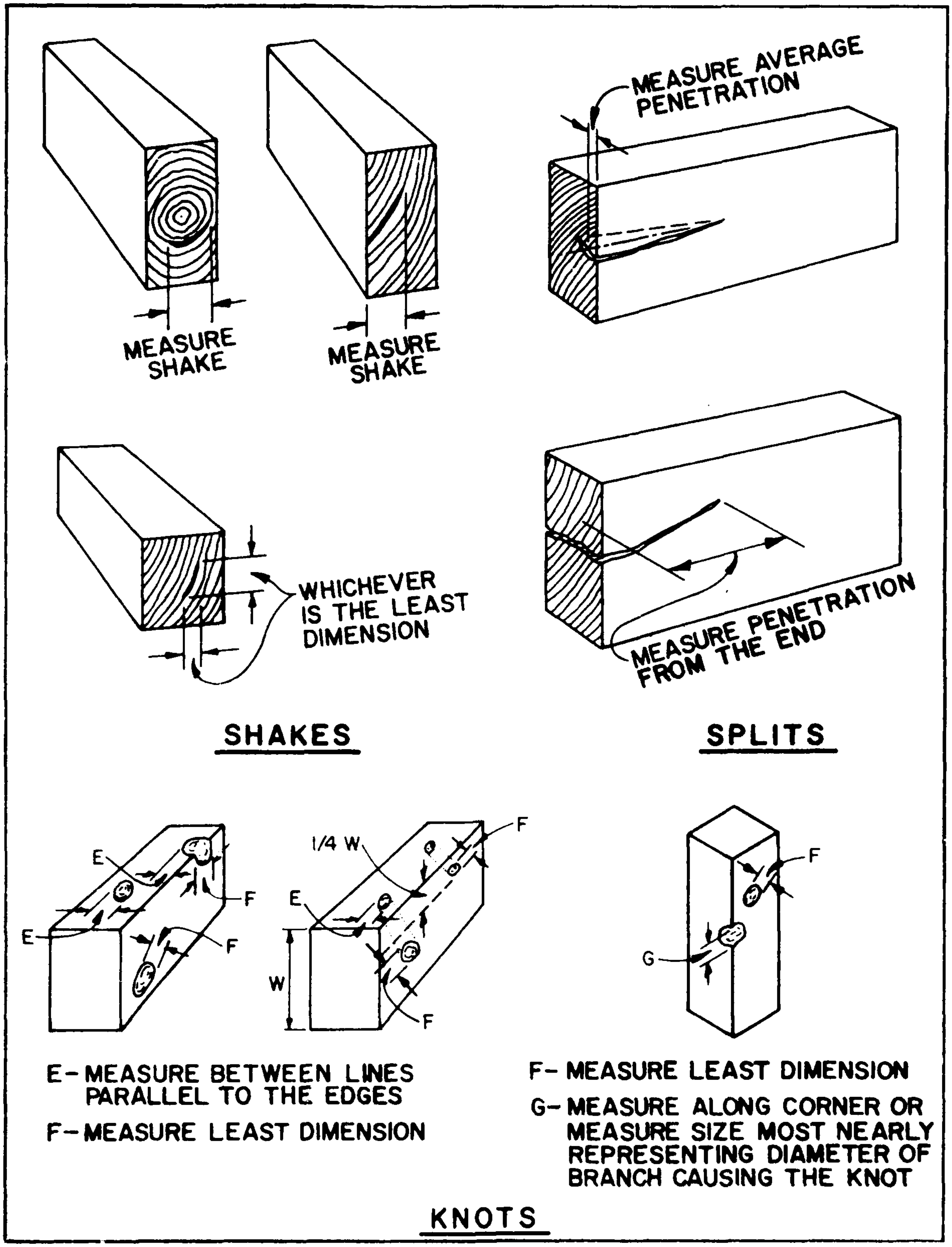


Figure 60. Defects affecting strength of lumber (American Institute Timber Construction, 1974).

and other strength reducing characteristics are described in sufficient detail that the procedures of ASTM D245 can be applied and working stresses can be assigned to the specified quality. It is common practice to give each grade a commercial designation such as No. 1 for best, No. 2 for next best. This means that the purchaser orders the commercial grade which qualifies for the values used in design.

(6) Machine Graded Lumber. While most structural lumber has design values assigned on the basis of visual grading to meet a minimum quality specification, there is a growing trend toward the nondestructive testing of lumber by machine. In this method a piece of lumber is passed flatwise through a series of loading rollers and the stiffness, or modulus of elasticity, is automatically recorded. Through correlation with previously established test data, bending strength and other strength properties are assigned to each piece tested. At present, machine grading is supplemented by visual grading particularly in the assignment of horizontal or longitudinal shear values.

(7) National Design Specification. The principal reference for working stresses for commercial grades of structural lumber is the National Design Specification for Wood Construction, available from the National Forest Products Association, Washington, D.C. The design value information in this specification is taken from the published rules written by the American Lumber Standards Committee (ALSC) and other grading rules writing agencies. When these values are used, each piece of lumber is required to be identified by the grade mark of a lumber grading or inspection agency recognized as being competent.

The National Design Specification provides for design of single member uses of lumber and other structural timbers, and also for repetitive member uses of lumber where load sharing is known to exist between repetitive framing members which are spaced not more than 0.6 meter (24 inches), are not less than 3 in number and are joined by floor, roof, or other load-distributing elements adequate to support the design load. For repetitive member uses, the design values in bending are higher than those for single member uses, as provided in the National Design Specification.

4. Selection of Timber Piles.

a. Round Timber Piles. Recommendations for the use of timber piles in foundations may be found in the American Wood Preservers Institute (1967). The ASTM D25-73, Standard Specifications for Round Timber Piles, classifies round timber piles according to the manner in which their load-carrying capacity is developed. There are two classes:

(1) Friction Piles. Friction piles are used when pile capacity is determined by the friction developed in contact with the surrounding soil, along with the compressive strength of the timber piles used. Table 29 from ASTM Standard D25-73, lists size requirements for friction piles.

(2) End-Bearing Piles. End-bearing piles are used when pile capacity is determined primarily by the end-bearing capacity of the soil at the pile tip, along with the compressive strength of the timber piles used.

Table 29. Friction piles - specified butt circumferences with minimum tip circumference (ASTM).

Length (m)	Required minimum circumference 914 mm from butt (mm)										
	559	635	711	787	889	965	1041	1118	1194	1270	1448
	Minimum tip circumferences (mm)										
6.1	406	406	406	457	559	635	711				
9.1	406	406	406	406	483	559	635	711			
12.2				406	432	508	584	660	737		
15.2					406	432	483	559	635	711	
18.3						406	406	472	549	625	803
21.3						406	406	406	411	488	665
24.4							406	406	406	406	554
27.4							406	406	406	406	495
30.5							406	406	406	406	457
33.5										406	406
36.6											406

Note: Where the taper applied to the butt circumferences calculate to a circumference at the tip of less than 406 mm, the individual values have been increased to 406 mm to ensure a minimum of 127 mm tip for purposes of driving.

Table 30 from ASTM Standard D25-73 (75), lists size requirements for end bearing piles.

Table 30. End-bearing piles - specified tip circumferences with minimum butt circumferences (ASTM).

Length (m)	Specified minimum tip circumference (mm)							
	406	483	559	635	711	787	889	965
	Minimum circumferences 0.9 meter from butt (mm)							
6.1	559	610	686	762	838	914	1 016	1 092
9.1	597	673	749	826	902	978	1 080	1 156
12.2	660	737	813	889	965	1 041	1 143	1 219
15.2	724	800	876	953	1 029	1 105	1 206	1 283
18.3	787	864	940	1 016	1 092	1 168	1 270	1 346
21.3	851	927	1 003	1 080	1 156	1 232	1 334	1 410
24.4	914	991	1 067	1 143	1 219	1 295	1 397	1 473
27.4	980	1 057	1 133	1 209	1 285	1 361	1 463	1 537
30.5	1 041	1 118	1 194	1 270	1 346	1 422	1 524	
33.5	1 107	1 184	1 260	1 336	1 412	1 549		
36.6	1 168	1 245	1 321	1 397	1 473			

b. Wood Sheet Pile. Wood sheet piles are sometimes used for groins, bulkheads and subterranean cutoff walls in a saltwater environment. Wood used as sheet piling is subject to environmental attack and therefore must be treated with preservatives if it is to have a useful life more than a few months. Wood sheet pile should be beveled at the bottom on one side and one edge to facilitate driving and to cause each succeeding pile to wedge firmly against the adjacent pile. Sheet pile should not be driven more than a meter. If deeper penetration is needed, the area along the line of piles should be excavated before driving so that the piles need be driven only a meter to final tip elevation. There are two types of wood sheet pile in general use. Members are sized according to the loads and conditions to be resisted by the sheeting.

(1) Tongue and Groove. Tongue and groove sheeting consists of planks milled so that on one edge there is a projecting tongue and on the opposite edge a groove into which the tongue of the adjoining plank is fitted when driven.

(2) Wakefield Sheet Piling. Wakefield sheet piling is made up of three layers of planks spiked or bolted together to form a sheet pile, so that the middle plank projects beyond the edges of the planks on each side, thus forming a tongue on one edge and a groove on the other (See Fig. 61).

5. Characteristics of Common Construction Species.

Woods normally used in the coastal zone are the domestic softwoods generally available in the United States: Douglas fir, southern pine,

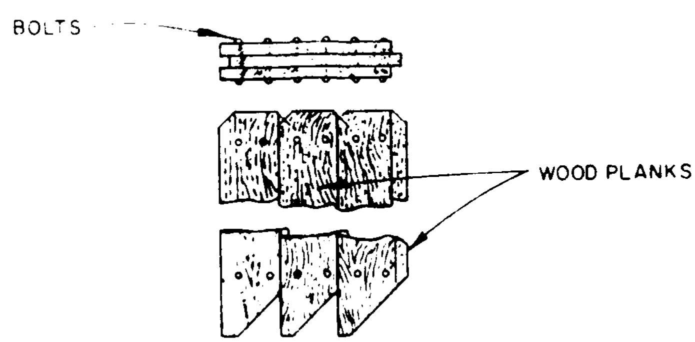


Figure 61. Wakefield sheet piling.

spruce, hemlock, redwood, cedar, and a number of species of pine, including lodgepole, ponderosa, and white. Hardwoods are less commonly used not because of inferior quality but because of cost or availability. Hardwoods, generally, are more difficult to treat with preservatives. However, special situations may call for hardwoods. For instance, an imported hardwood called greenhart is gaining some acceptance for use as fender piles because it appears to be fairly resistant to marine borers in its untreated state. Tables 31 and 32 list significant characteristics of domestic softwoods and hardwoods, respectively.

6. Destructive Biota.

a. General.

Although there are many life forms that may eat, live in, or make use of wood in a way that may be called destructive, many are so rare or do so little damage during the useful life of wood structures that they can be ignored relative to the use of wood in the coastal zone. Those that most

Table 31. Domestic softwoods.

General characteristics	Douglas Fir	Redwood	Cedar	Spruce	Southern Pine
Shrinkage in volume from green to ovendry (pct)	10.9	11.5	11.2	10.4	12.4
Modulus of rupture MPa	43.7 (green)	51.4 (green)	41.6 (green)	31.4 (green)	44.1 (green)
Modulus of Elasticity GPa	7.798 (green)	7.591 (green)	5.199 (green)	5.971 (green)	7.860 (green)

Table 32. Domestic and imported hardwoods.

Domestic				
General Characteristics	Oak	Maple	Ash	Birch
Shrinkage in volume from green to ovendry (pct)	12.7 to 17.7	12.0 to 14.5	11.7	15.0 to 16.8
Modulus of rupture MPa	49.5 to 73.8 (green)	40.1 to 62.5 (green)	41.4 to 68.9 (green)	59.2 (green)
	54.2 to 77.3 (dry)	105.2 (dry)	108.0 (dry)	133.8 (dry)
Modulus of elasticity GPa	6.047 to 11.63 (green)	6.502 to 10.16 (green)	7.102 to 10.20 (green)	10.27 to 10.64 (green)
	9.108 to 14.36 (dry)	12.14 to 12.95 (dry)	9.618 to 12.26 (dry)	16.52 (dry)
Imported				
General Characteristics	Greenhart			
Shrinkage in volume from green to ovendry (pct)	3			
Modulus of rupture MPa	123.4 (green) 206.8 (dry)			
Modulus of elasticity GPa	20.00 (green)			

seriously affect the useful life of wood are the shipworms (teredos) of the family Teredinidae and small (2 millimeters) crustaceans of the genus Limnoria. These marine biota are generally more active in clean water with high dissolved oxygen. On land, the most destructive insects are termites. Also on land but more in air, and very destructive in the presence of moisture or intermittent wetting are the fungi and bacteria. Preservative treatment can reduce the destructive effects of the various biota and extend the useful life of wood but cannot completely prevent the attacks. Cracks or holes in the wood or leaching of the preservatives will eventually allow access for some marine borer or nest of termites.

b. Teredinidae. These are marine bivalve mollusks that have evolved into a long wormlike shape with its "shell" parts having become a set of grinders at one end that the teredo uses to bore holes in wood. An adult can be 50 to 100 millimeters long and 5 to 10 millimeters in diameter (Fig. 62). The individual enters the wood as a larva by making a small hole that is never enlarged at the surface. As it grows, the teredo bores a larger hole into the wood at the rate of 20 to 300 millimeters per month to accommodate its whole body and apparently to feed itself (Fig. 63). An infestation of teredos can destroy an untreated pile at the mud line in 5 to 6 months (Kofoid and Miller, 1927). Species found in abundance in U.S. waters are *Teredo diegensis* and *Teredo navalis*. Teredos are sensitive to coal tar creosote treatment.

c. Limnoria. These are small marine crustaceans about 2 millimeters long and less than 1 millimeter wide (Fig. 64) that either enter the wood in the adult stage or are hatched and remain in the same piece of wood. They use the wood as habitat and apparently as food supply because they continue to bore holes after they are securely entrenched in the wood (Ray, 1959). They bore at the rate of about 0.5 millimeter per day (Kofoid and Miller, 1927). At this rate, a heavy infestation of limnoria could eat through a 30-centimeter untreated pile in about a year. One species, *Limnoria tripunctata*, is present off most of the U.S. coastline (see Fig. 65). A subspecies, *Tripunctata mengies* is found all along the Atlantic seaboard and in the Pacific Ocean from the southern end of the South Island of New Zealand to several hundred miles north of Vancouver, Canada. *Limnoria tripunctata* is particularly troublesome because it apparently is not repelled by coal tar creosote preservative (American Society for Testing Materials, 1957). Where *L. tripunctata* is present the dual treatment, described in paragraph 6, Preservative Treatment of Wood, is required. Figure 66 shows the damage that can occur from limnoria attack.

d. Termites. The principal termite species attacking wooden structures in the United States is a subterranean type named *Reticulitermes hesperus*. The typical life cycle of this species starts with winged reproductive adults that fly from the nest for the purpose of establishing new colonies. When a pair finds a suitable environment they start a colony. In 5 or 6 years, a colony may contain several thousand individuals (Palermo, 1951).

Termites are antlike insects about 5 millimeters long that spend their lives inside an earth nest or gnawing tubes through available wood (except for the winged adults). Termite damage is not evident to casual observation because the outer layer of wood is left untouched for their own protection. The usual evidence of their presence are the piles of fecal pellets that

Figure 62. Teredo or shipworm (Ray, 1959).

Figure 63. Typical work of the teredo (Ray, 1959).

Figure 64. Live limnoria in their burrows (Ray, 1959).

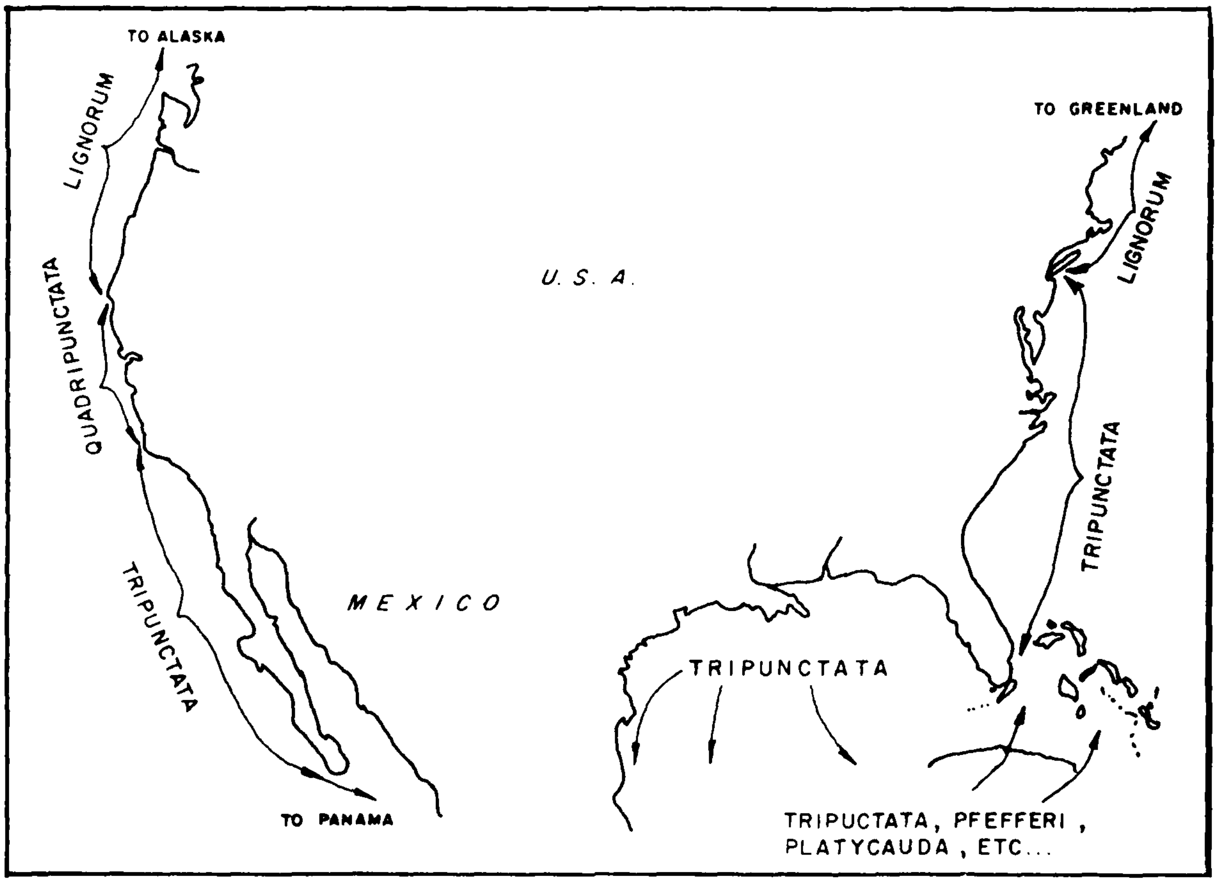
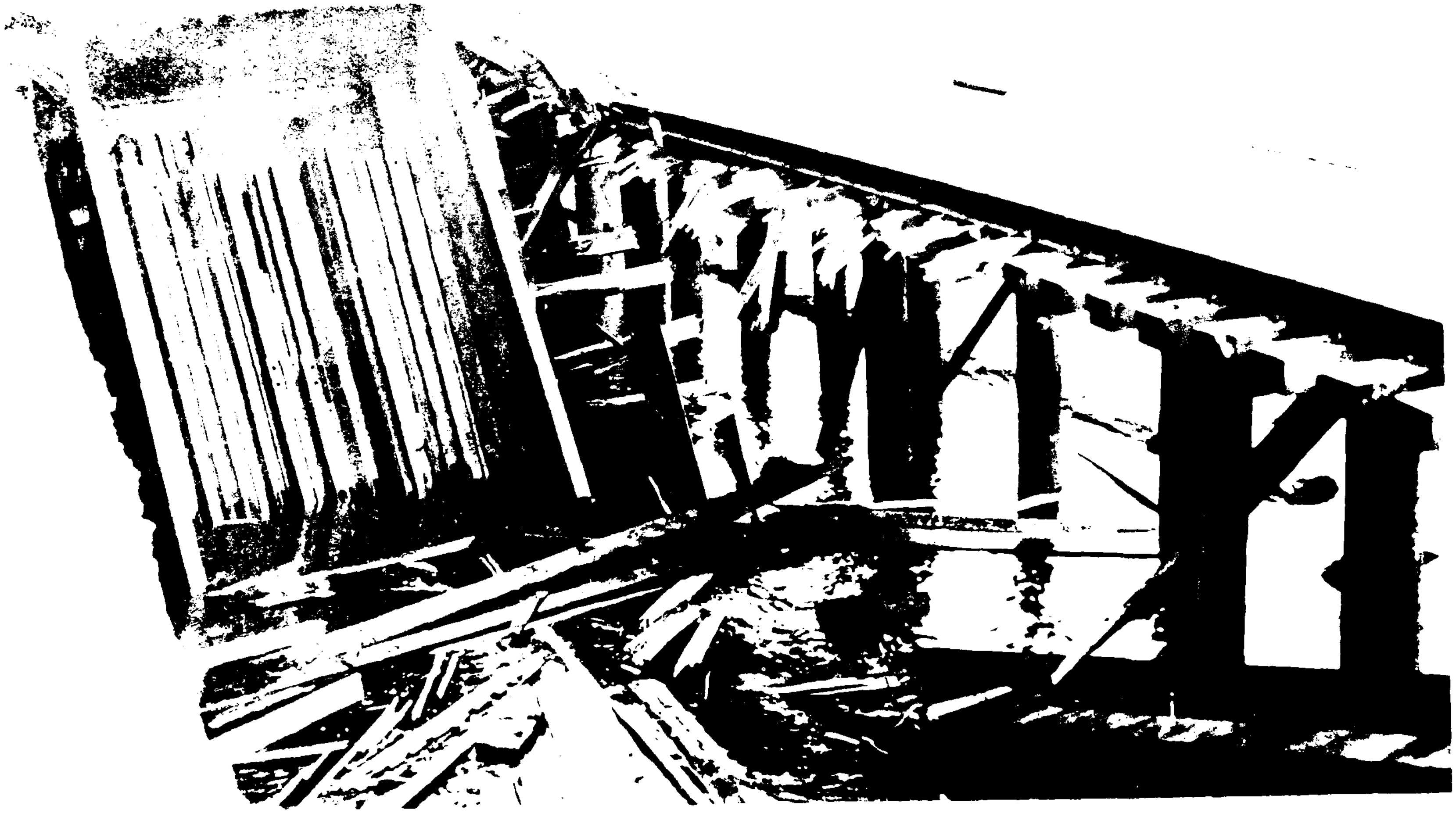


Figure 65. Distribution of limnoria in North America (ASTM, 1957).



[illegible] collapse of wood wharf under railroad gondolas
[illegible] Limnoria attack on piles. (L.A. Harbor photo)

are pushed out of the way through small ventholes about 1 millimeter in diameter in the wood. A structure attacked by termites will eventually fail unless the infestation is discovered early and the termites destroyed.

Termite control can be accomplished in several ways. Separation of structural wood from the ground and removal of all cellulose material from the ground in the vicinity of the structure are accomplished in the design and construction phases. Dry ground, good ventilation, and exposure to sunlight also discourage termites from nesting. If contact with the ground cannot be avoided as in the case of power poles, pressure treatment with preservatives will discourage termites. Poison can be injected into the wood and nesting areas where termites are established.

c. Fungi. The decay fungi, which are of primary concern, consist of microscopic threadlike strands known as hyphae; these aggregate into a mass called mycelium. The mycelium under suitable conditions form fan sheets, especially when developing in a very moist locality. These may give rise to the fruiting body of the fungus which, in the case of the decay fungi, is relatively flat. These fruiting bodies bear enormous numbers of microscopic spores which are similar in function to the seeds of higher order plants. The spores are readily distributed by water or air currents, or by men and animals. Spores germinate and penetrate wood by means of hyphae. The fungus may also be spread from decayed material to sound material by the hyphae.

In the United States there are many species of fungi that cause wood decay. Two important species are the building poria, *Poria incrassata*, and the tear fungus, *Merulius lachrymans*. The tear fungus is more common in northern United States and Canada; the poria fungus prevails in the south and west (Thomas, 1951). Timber destroying fungi require both moisture and oxygen at a temperature of about 20° to 36° Celsius (68° to 97° Fahrenheit) for optimum growth. Therefore, wood that is kept very dry will not decay nor will wood that is submerged where the oxygen is excluded. Because wood must be kept moist, the term "dry rot" is a misnomer for the crumbly brown rot that results from the action of fungi. Figure 67 shows specimens of wharf timbers heavily damaged by fungi.

Control of fungi in wood structures can be accomplished by proper design and by chemical treatment. Design criteria should anticipate meteorogical conditions such as fog, rain, or dew which may deposit moisture on wood surfaces. Wood structures should be designed to provide for drainage of wood surfaces and eliminate joints and pockets where moisture can collect. Where exposure to moisture is severe and cannot be eliminated by design, pressure treatment with a wood preservative is required. Coal tar creosote, copper napthenate, pentachlorophenol and salt preservatives such as chromated zinc chloride are used separately or in combination for fungi control.

7. Preservative Treatment of Wood.

a. General. To extend the life of wood for both economical and practical use in the coastal zone, it must be protected from its natural enemies--fungi, bacteria, insects, and marine organisms. Effective preservative treatments have been found to discourage the natural enemies and extend the useful life of wood to about four to five times that of untreated wood.

Figure 67. Specimens of wharf timbers damaged by dry rot (fungus) (photo courtesy of Los Angeles Harbor Department).

Untreated wood can be used effectively for temporary structures and facilities.

b. Pressure Processes. The most effective method of treating wood with preservatives is by means of pressure. There are a number of pressure processes that employ the same general principle but differ in the details of application. Treatment includes loading the timber on tramcars, which are run into a large steel cylinder, bolting the cylinder door, and pressure applying the preservative until the required absorption has been obtained. Two principal types of pressure treatment, the full-cell and empty-cell, are in common use (U.S. Department of Agriculture, 1952).

(1) Full-Cell Processes. In pressure treatments with the so-called "full-cell" or Bethell process, a preliminary vacuum is first applied to remove as much air as practicable from the wood cells. The preservative is then admitted into the treating cylinder without admitting air. After the cylinder is filled with preservative, pressure is applied until the required absorption is obtained. A final vacuum is commonly applied immediately after the cylinder has been emptied of preservative to free the timber (or charge) of dripping preservative. When the timber is given a preliminary steaming-and-vacuum treatment, the preservative is admitted at the end of the vacuum period following steaming.

It is impossible to remove all the air from the wood cells regardless of the method of treatment employed. For this reason, even under the most favorable conditions, there is some unfilled airspace in the cell cavities of the treated wood after impregnation by the full-cell process.

(2) Empty-Cell Processes. Two empty-cell treatments, the Lowry and the Rueping, are commonly used, both of which depend on compressed air in the wood to force part of the absorbed preservative out of the cell cavities after preservative pressure has been released. In the Lowry process, which is also designated as the "empty-cell process without initial air," the preservative is admitted to the treating cylinder at atmospheric pressure. When the cylinder is filled, pressure is applied and the preservative is forced into the wood against the air originally in the cell cavities. After the required absorption has been obtained, pressure is released, a vacuum is drawn, and the air under pressure in the wood forces out part of the preservative absorbed during the pressure period. This makes it possible, with a limited net retention, to inject a greater amount of preservative into the wood and to obtain deeper penetration than when the same net retention is obtained with the full-cell process. The Lowry process is convenient to use in any pressure-treating plant, since no additional equipment is required.

The Rueping process is called "empty-cell process with initial air"; this process differs from the Lowry empty-cell process in that air is forced into the treating cylinder before the preservative is admitted. The air pressure is then maintained while the cylinder is filled with preservative; thus, the wood cells are left more or less impregnated with air pressure.

c. Classification of Wood Preservatives. Wood preservatives may be grouped into two broad classes; preservative oils and waterborne preservatives. Each of these classes may be further subdivided in various ways. For example, preservative oils include petroleum refining byproduct oils

such as coal-tar creosote and other creosotes, mixtures of coal tar creosote with coal tar, petroleum, or other oils, solutions of toxic chemicals such as pentachlorophenol or copper naphthenate in selected petroleum oils or other solvents, and various mixtures of these solutions with the byproduct oils and mixtures. The waterborne preservatives include solutions of single chemicals such as chromated zinc chloride (CZC) or chromated copper arsenate (CCA), which are not resistant to leaching, and various formulations of two or more chemicals that react after impregnation and drying to form compounds with limited solubility and sometimes with high resistance to leaching.

Preservatives vary greatly in effectiveness and in suitability for different purposes and use conditions. The effectiveness of any preservative depends not only on the materials of which it is composed, but also on the quantity injected into the wood, the depth of penetration, and the conditions to which the treated material is exposed in service.

(1) Coal-Tar Creosote. Coal-tar creosote is defined by the American Wood Preservers Association as a preservative oil obtained by the distillation "of coal tar produced by high-temperature carbonization of bituminous coal; it consists principally of liquid and solid aromatic hydrocarbons and contains appreciable quantities of tar acids and tar bases; it is heavier than water; and it has a continuous boiling range of at least 125° Celsius, beginning at about 200° Celsius." Coal-tar creosote is highly effective and is the most important and most extensively used wood preservative for general purposes. Coal-tar creosote solutions vary and usually contain from 30 to 70 percent of coal tar by volume; the most prevalent mix contains 50 percent coal tar.

(2) Chemicals Dissolved In Solvents Other Than Water. Preservatives composed of toxic chemicals carried in nonaqueous solvents, such as petroleum-oil distillates, are now being used to an increasing extent. These were originally devised for the purpose of providing a clean treatment without causing swelling of the wood and were originally applied by nonpressure methods.

A shortage of cresote that developed during World War II created an active interest in the use of these preservatives as a possible substitute for creosote, especially in the pressure treatment of poles. Particular attention was directed to the chlorinated phenols, which are known to have a high degree of toxicity. Pentachlorophenol is the best known and most widely used in this group. Other preservatives of this type, which in the past have been largely limited to use in surface treatments, are the metallic naphthenates, such as copper naphthenate. The latter has also been used to a limited extent for pressure-treated poles.

Although some of these toxic chemicals, particularly pentachlorophenol, have given excellent results over a considerable period of time, service records are still inadequate to evaluate them completely in comparison with coal-tar creosotes.

(3) Waterborne Preservatives. A variety of chemicals in water solution are used as wood preservatives. These include zinc chloride, sodium fluoride, arsenic in various forms, copper sulfate, and similar toxic chemicals. Most of these salts are used in combination with one or more

other chemicals, frequently including a chromium compound. Chromated zinc chloride (CZC), which is composed of a mixture of zinc chloride and sodium dichromate, has come into wide use in recent years. The preservative is now much more extensively used than straight zinc chloride, which was formerly the most widely used waterborne salt. A less widely used compound, Fluoro-chrome-arsenate-phenol (FCAP), is one of the preservatives listed in the current standards and government specifications.

Arsenic compounds have been used as preservatives for many years. They are important ingredients of a number of proprietary preservatives, some of which have demonstrated high effectiveness and are extensively used. Three effective compounds commonly used are chromated copper arsenate (CCA), acid copper chromate (ACC), and ammoniacal copper arsenate (ACA). Three types of CCA are specified in Interim Federal Specification (U.S. Department of Agriculture, 1974). The type is chosen according to availability and economics.

Copper sulfate, although extensively used in Europe for many years and demonstrated to be moderately effective in retarding decay, has found little use for wood preservation in the United States except in certain proprietary preservatives, in which it is combined with other chemicals. Several of these preservatives are of high effectiveness and extensively used. Copper sulfate is corrosive to iron and steel and, therefore, cannot be used alone in ordinary treating equipment.

(4) Proprietary Preservatives. Various patented or proprietary preservatives are sold under trade names for pressure treatment. For the most part they are composed of various waterborne salts and are injected in water solutions. Others employ a volatile solvent to carry the toxic substance into the wood. Some of the waterborne preservatives contain chemicals that are intended to react after injection into the wood and to form substances that are of low solubility and resistant to leaching.

Wolman salts is one of several proprietary names for a waterborne salt, chromated copper arsenate (CCA), also known as "green-salt." Chemonite is another proprietary name for ammoniacal copper arsenate (ACA). Other proprietary names for preservatives can be found in the American Wood Preservers Association Standard (AWPA) M9. It lists a number of proprietary names for each of the standard preservatives.

8. Specific Applications for Treated Wood.

a. General. Tables 33 and 34 indicate the amount of preservative to be retained in various wood forms using approved practices for preservative treatment with creosote and solutions containing creosote, pentachlorophenol, and waterborne preservatives. The net retentions in the tables are minimum penetration requirements. Higher net retentions may be needed for severe use conditions and should be specified when applicable. Data in the tables are taken from Federal Specification TT-W-571J.

Coal-tar creosote, creosote-coal tar solution, creosote-petroleum solution, and pentachlorophenol in heavy petroleum solvent and the four waterborne preservatives, ACA, and CCA Types A, B, and C are ordinarily to be

Table 33. Preservative retention for timber treatment (from AWPA C2 and C18).

Application	Types of Preservative	Retention by SPECIES (pcf): Southern Pine, Coastal Douglas Fir[2], Western Hemlock[2]	Western Larch, Interior Douglas Fir, Ponderosa Pine, Redwood, Jack Pine, Lodgepole Pine, White Pine, Red Pine, Sugar Pine	Oak	Gum
Above Ground	Creosote[1]	8.0[3]	8.0[3]	5.0 or 6.0[4]	6.0
	Pentachlorophenol	.4[3]	.4[3]	.25 or .3[4]	.3
	ACC, ACA, CCA	.25[3]	.25[3]	.25	.25
	CZC	.45[3]	.45[3]	.45	.45
	FCAP	.25[3]	.25[3]	.25	.25
Freshwater Soil Contact	Creosote[1]	10.0[5]	10.0	6.0 or 7.0[4]	8.0
	Pentachlorophenol	.5[5]	.5	.3 or .35[4]	.4
	ACC	.5[5]	.5	.5	.5
	CCA or ACA	.4[5]	.4	.4	.4
Saltwater Contact – Splash Zone	Creosote[1]	12.0	-----[6]	-----[6]	-----[6]
	Pentachlorophenol	.6			
	CCA or ACA	.6			
Saltwater Contact – Submerged – Single	Creosote[1,2]	25.0[6,7]	25.0[6,7]	10.0[6,7]	12.0[6,7]
	CCA or ACA	2.5[8]	2.5[6,8]	NR[6,8]	NR[6,8]
Saltwater Contact – Submerged – Dual[9]	Creosote[1]	20.0			
	CCA or ACA	1.5			

[1]Includes creosote-coal tar.
[2]Creosote-coal tar not recommended for single treatment of these woods.
[3]In saltwater atmosphere, above splash zone, use retentions for "Freshwater and Soil Contact."
[4]For members under 5 inches (13 cm) thick.
[5]In soil contact in saltwater splash zone or atmosphere, use retentions for "Splash Zone."
[6]AWPA C2 lists treatments for these woods "Subject to Marine Borer Exposure," but AWPA C18 does not recommend them for saltwater use. NR: Not recommended.
[7]Teredo is present with no to light limnoria activity.
[8]Limnoria activity is moderate to heavy but pholads are absent.
[9]Limnoria is present with teredo or pholads.

Table 34. Preservative retention for treatment of wood piles (from AWPA C3).

Application		Types of Preservative	Retention by SPECIES (pcf): Southern Pine	Coastal Douglas Fir	Oak[3]	Red Pine[3] Ponderosa Pine[2] Jack Pine[2]	Lodgepole Pine Western Larch Interior Douglas Fir
Foundation, Land, Freshwater		Creosote[1]	12.0	17.0	6.0	12.0	17.0
		Pentachlorophenol	.6	.85	.3	.6	.85
		CCA or ACA	.8	1.0	NR[4]	.8	1.0
Saltwater (Submerged)[2,3]	Single	Creosote[1]	20.0[5] or 25.0[6]	20.0[5] or 22.0[6]	10.0[3,5]	20.0[2,3,5]	
		CCA or ACA	2.5[7]	2.5[7]	NR[4,7]	2.5[2,3,7]	
	Dual[8]	Creosote[1]	20.0	20.0			
		CCA or ACA	1.0	1.0			

[1]Includes creosote-coal tar.
[2]Ponderosa and jack pine piles are not used in saltwater environments. Applies only to red pine piles.
[3]Fed. Spec. TT-W-571J does not specify oak and red pine piles for saltwater use.
[4]Not recommended.
[5]Teredo is present with no to light limnoria activity.
[6]Fed. Spec. TT-W-571J recommends these where teredo is present with light limnoria activity. Navy prefers these over dual treatment for fender piles.
[7]Limnoria activity is moderate to heavy but pholads are absent.
[8]Limnoria is present with teredo or pholads.

used for wood exposed to severe weathering conditions, such as contact with soil or water and for important aboveground structures exposed to the weather. Because oil-type preservatives afford protection against weathering and checking as well as against decay, they are generally preferable to waterborne preservatives for the treatment of sawed wood that is to be used in contact with the ground. If cleanliness, freedom from odor, or paintability is essential, either of the four waterborne preservatives mentioned above may be expected to give good protection to sawed wood that is selected for its receptiveness to treatment and treated to meet the minimum penetration requirements. The same four preservatives may be used for wood in contact with saltwater where limnoria are the only threat. Pentachlorophenol in a volatile petroleum solvent (Table 33) is ordinarily to be used in aboveground structures, particularly where cleanliness and paintability are required. All the waterborne preservatives (Table 34) are suitable for such use. Pentachlorophenol in a light petroleum solvent is also generally limited to aboveground use especially where moderate cleanliness is desired and freedom from residual solvent is not essential. If water repellency also is desired in order to avoid surface damage due to wetting during storage, it should be stipulated by the purchaser. In some harbors, conditions are highly favorable for limnoria, and the life of creosoted piling may be extended by mechanical barriers. AWPA Standard C3 includes a dual treatment that is recommended for trial in harbors where experience has shown that a high limnoria hazard exists along with other organisms.

Painting of treated wood involves special considerations. Wood treated with creosote, solutions containing creosote, and pentachlorophenol in heavy petroleum solvent cannot ordinarily be painted satisfactorily. When requested it can be conditioned by the producer to improve its cleanliness. Difficulties may be encountered in painting wood treated with pentachlorophenol in a light petroleum solvent. Wood treated with waterborne preservatives should be properly seasoned after treatment and may require light brushing or sanding in order to provide a paintable product. Since "cleanliness" is a relative term, it is recommended that the purchaser make known his specific requirements and the end use of the material, and that the supplier be required to furnish evidence that the material be suitable for that use. In the absence of accepted methods for determining cleanliness, paintability, and water repellency of pentachlorophenol-treated wood, the purchaser may elect to use arbitrary test methods which should be described to the supplier.

b. Timbers and Lumber.

(1) Functioning Environment. The treatment required for marine timbers and lumber depends on the environment in which they function. Timbers subject to the marine environment but not submerged or intermittently submerged, are treated differently than those that are submerged. The reason being that submerged timbers are subject to marine borer attack and must be treated according to the anticipated attack.

Unsubmerged timbers are highly subject to fungus attack, particularly where water spray or airborne moisture can frequently wet them, but they cannot be attacked by marine borers.

An example of submerged use would be the framing and bracing members of a wood pier. Another would be wales, particularly the lower wales of

fender piles and wales at the top of wood groins. These are frequently located at or below the water level. The planks of Wakefield piling used as a groin and wood cribbing below water are other examples.

When timber and lumber are used above the water but near enough to be frequently wetted by splash and spray they would be in the spray or splash zone. Pier decks and wood fittings such as handrails are frequently in this use zone. Timber bulkheads and cribbing above water are also frequently in the splash zone.

Where wood is used away from the immediate contact with saltwater or its splash and spray, two different treatments are called for. They are pressure treatments that have different retention requirements depending on whether the wood is placed in contact with the soil or above the soil in air. Retention requirements for these uses are shown on Table 33.

Examples of wood in contact with soil would be bulkheads and retaining walls using Wakefield piles or horizontal planking supported by vertical piles. Sometimes boardwalks are incorporated into a bulkhead structure and these frequently are in firm contact with the soil. Sand fences and cribs placed above the tide line are usually in direct contact with the soil.

Wood in air is probably best visualized in causeway decking (far enough removed from the water to be free of the direct influence of splash and mist) buildings, towers, navigation aids and other such structures built on piles or concrete foundations. Whatever the foundation, wood in air must be clear of the ground by at least 200 millimeters (8 inches) and well ventilated. In the southern United States or in especially warm and moist climates, additional clearance should be considered (ASCE, 1975).

(2) Preservative Retention Standards. The adequacy of preservative treatment may be determined by the quantity of preservative retention or by its penetration into the wood.

(a) Retention By Assay. The quantity of preservative required for adequate protection is given by the American Wood Preservers Association (AWPA) in pounds per cubic foot (pcf). The retained quantity is measured by assaying the contents of core samples.

Timber and lumber used in submerged locations should be pressure treated using the full cell process to achieve retention equal to or greater than the amounts shown in Table 33. In those parts of the world where teredo and pholad attack is expected and where *Limnoria tripunctata* attack is not prevalent, creosote or creosote-coal tar treatment will provide adequate protection. Where *L. tripunctata* attack is expected, and where either teredo or pholad attack is expected, the dual treatment with creosote or creosote-coal tar and either CCA or ACA preservatives to the retentions shown on Table 34 will give the best protection known (AWPA C3).

Timber and lumber in the splash zone can be protected by using either of the oil base preservatives, creosote or creosote-coal tar or one of the waterborne preservatives CCA or ACA to the retentions shown on Table 33. The creosote or creosote-coal tar preservatives are usually preferred because the waterborne preservatives are subject to leaching.

Creosote and creosote-coal tar mixtures are commonly employed for sawed material (such as bridge timbers) used under relatively severe conditions. Retentions specified for such timbers vary from about 942 to 3 927 newtons per cubic meter (6 to 25 pounds per cubic foot), about 1 570 to 1 890 newtons (10 to 12 pounds) being most common. Both empty-cell and full-cell methods are employed, depending on the amount of sapwood, retention required, size of timbers, and similar factors. The full-cell process is commonly employed in the treatment of resistant heartwood timbers and timber for use in salt-water.

Waterborne salts are widely applied in the treatment of sawed lumber under conditions that make it impractical to employ preservative oils.

Specifications for retentions of both preservative oils and water-borne salts often fail to take into consideration the relation of the timber dimensions to penetration and retention. The specifications may require a net retention in large heartwood timbers that cannot be obtained because of the small ratio of surface area to volume, although the same retention might be obtained without difficulty in heartwood timbers of tie size or smaller or in large-size timbers containing a large proportion of sapwood. In timbers containing 50 percent or more sapwood, it is recommended that at least 1 570 newtons per cubic meter of preservative oil be specified.

(b) Retention by Penetration. The AWPA standards for adequate penetration of the preservative indicate the required penetration in inches or percent of the thickness of the sapwood, whichever is greater. Penetration requirement of preservatives in timbers and lumber generally varies according to species. However, for some species it also varies by size. Timbers and lumber smaller than 5 inches (127 millimeters) require less penetration when the species is coastal Douglas fir, hemlock or pine species other than southern pine and ponderosa. Requirements for penetration are found in tables of AWPA Standard C2. The following are representative examples of preservative penetration requirements found in the tables. For use above ground or in freshwater, the penetration required for southern pine is 63.5 millimeters (2.5 inches) or 85 percent of the sapwood for all sizes. Coastal Douglas fir would require a penetration of 12.7 millimeters (0.5 inch) and 90 percent of the sapwood for sizes 5 inches (127 millimeters) and larger but for sizes under 5 inches the requirements would be 10.16 millimeters (0.4 inch) and 90 percent of the sapwood. Oak, for the same uses, would have only the percentage requirement with white oak requiring 95 percent of sapwood and red oak requiring 65 percent of annual rings. In the marine environment, the penetration requirements would be similar for each preservative of the dual treatment.

(c) Treatment of Cuts and Holes. Insofar as practical, wood pieces should be trimmed, dapped, bored and counterbored before pressure treatment because field treatment cannot match the thorough penetration and distribution of preservatives obtainable in the pressure retort. However, it is not always possible and practical to avoid all field cuts and bores. When pretreated wood is cut in the field it is essential that the exposed wood be generously mopped with the same preservatives. The top faces of field cuts are particularly vulnerable to fungus attack and should be given extra careful field treatment. Wood submerged in saltwater is vulnerable

to marine borers that can enter the wood in very small cracks or exposed areas.

c. Piles.

(1) General. The principal woods used for piling are southern pine and coastal Douglas fir, although a few other woods, such as red pine, lodgepole pine, western larch, and oak, are used in some localities. No untreated wood, commercially available for pilings, either domestic or imported, will resist borer attack for more than several years. However, one species of tropical tree known as greenheart (*Ocotea rodiaei* or *Nectandra rodiaei*), which is not treatable, may last 2 or 3 years longer than treated Douglas fir, in the same water. Timber piles should conform to the requirements of ASTM Standard D25.

Untreated pine and fir piles usually last no longer than 2 years in the ocean, often less than 1 year where marine borers, such as *L. tripunctata*, are present in great numbers. Treated piles have a life expectancy averaging 8 to 10 years where *tripunctata* are present. *Limnoria tripunctata* was selected as an example because this is the only known species of Limnoria which will attack and destroy heavily creosoted piling (Civil Engineering Laboratory (CEL), 1974)).

The Forest Products Laboratory has tested a large number of preservatives to study their effectiveness in protecting wood against marine borers. Results obtained in these experiments, as well as experience in general, have shown that heavy retentions of coal-tar creosote are essential if the best protection is to be obtained (USDA, 1952). The heavy retentions ensure better penetrations and also furnish a reserve supply of creosote to provide against early depletion by leaching. Over much of the coastal region of the United States, marine timbers are exposed to severe borer attack, and it is poor economy to specify retentions that will not give the maximum protection under such conditions. Specifications for such timbers should require treatment to refusal by the full-cell process, and the specified retention should be th· minimum that will be accepted. No maximum should be specified.

The Civil Engineering Laboratory (CEL, 1974) reports that a compound that is toxic to *L. tripunctata* does not prevent *Teredo diegensis* attack and a compound that is toxic to *T. diegensis* is not effective against *L. tripunctata*. Experiments by CEL indicate that a dual treatment of wood piles should be used in moderate or warm waters to effectively defend against marine borer attack. The dual treatment consists of metallic salts, either ammoniacal copper arsenate (ACA) or chromated copper arsenate (CCA) and coal-tar creosote. A 157-newton per cubic meter (1.0 pound per cubic foot) treatment of metallic salts is applied in water solution. After drying, the wood is pressure treated with coal-tar creosote to a 3 140-newton per cubic meter (20 pound per cubic foot) retention. The above treatment may be specified as conforming to American Wood Preservers Association Standard C3. This treatment significantly increases the expected life of wood piles used in moderate or warm waters but it also reduces the strength and toughness of the wood. Eaton, Drelicharz and Roe (1978) of the Civil Engineering Laboratory report that dual-treated piles lose 27 to 54 percent of their untreated flexural strength, measured as modulus of rupture, and about 50 percent of their untreated flexural toughness, measured as energy absorbed per unit

volume. They recommend creosote treatment alone rather than dual treatment for fender piles in cases where breakage from impact may limit the useful life before marine borer attack. Appendix B describes their results, including effects on other mechanical properties.

In northern waters or where attack by *L. tripunctata* is not anticipated and *Teredo* is the only threat, pressure treatment of 3 140 newtons per cubic meter of coal-tar creosote would be sufficient. The effects on properties are described in Appendix B. Other chemicals, such as pentachlorophenol, should not be used in seawater because this chemical will hydrolize. That is, the presence of water will split the chemical bonds and unite with the radical ions of the original compound to form acids and bases.

Table 34 shows preservative retention requirements as set forth in AWPA Standard C3 for single and dual treatment of wood species most likely to be used for piles in the United States. Preservative retentions in pounds per cubic foot are measured by assay of bore samples.

Requirements for adequate preservative treatment of piles include minimum penetrations. Penetration requirements for various species of wood piles and use conditions are also set forth in AWPA Standard C3. Penetration tests are made by gauging the penetration distance from the outside face of the pile. Representative preservative penetration requirements for the wood species most frequently used for piles are presented in Table 35.

Table 35. Representative preservative penetration requirements.

	Foundation or Freshwater	Saltwater Dual Treatment
Southern Pine	7.6 cm or 90 pct of the sapwood	8.9 cm or 90 pct of the sapwood
Coastal Douglas Fir	1.9 cm and 85 pct of the sapwood	2.5 to 4.4 cm and 85 pct of the sapwood.

(2) Treatment of Pile Cutoffs, Framing Cuts and Holes. After driving treated wood piles in a wood wharf or another structure, excess wood in the piles is sawed off at the desired elevation. This exposes untreated wood at the cutoff, which necessitates some kind of preservative treatment in place. The usual method is to swab the cutoff with creosote, cover that with Irish flax, and add another coat of creosote before placing the pile cap. On inspection, cones of dry rot have been found in the pile tops with the foregoing treatment, after only a few years' service.

A method which has adequately protected the cutoff areas and is inexpensive consists of boring five or six 19.1-millimeter (0.75 inch) holes, about 25.4 millimeters (1 inch) apart in a circular pattern, in the untreated area of the cutoff. This is shown in Figure 68. The holes are then filled with a 50-50 mix of liquid coal tar and creosote. A layer of Irish flax is

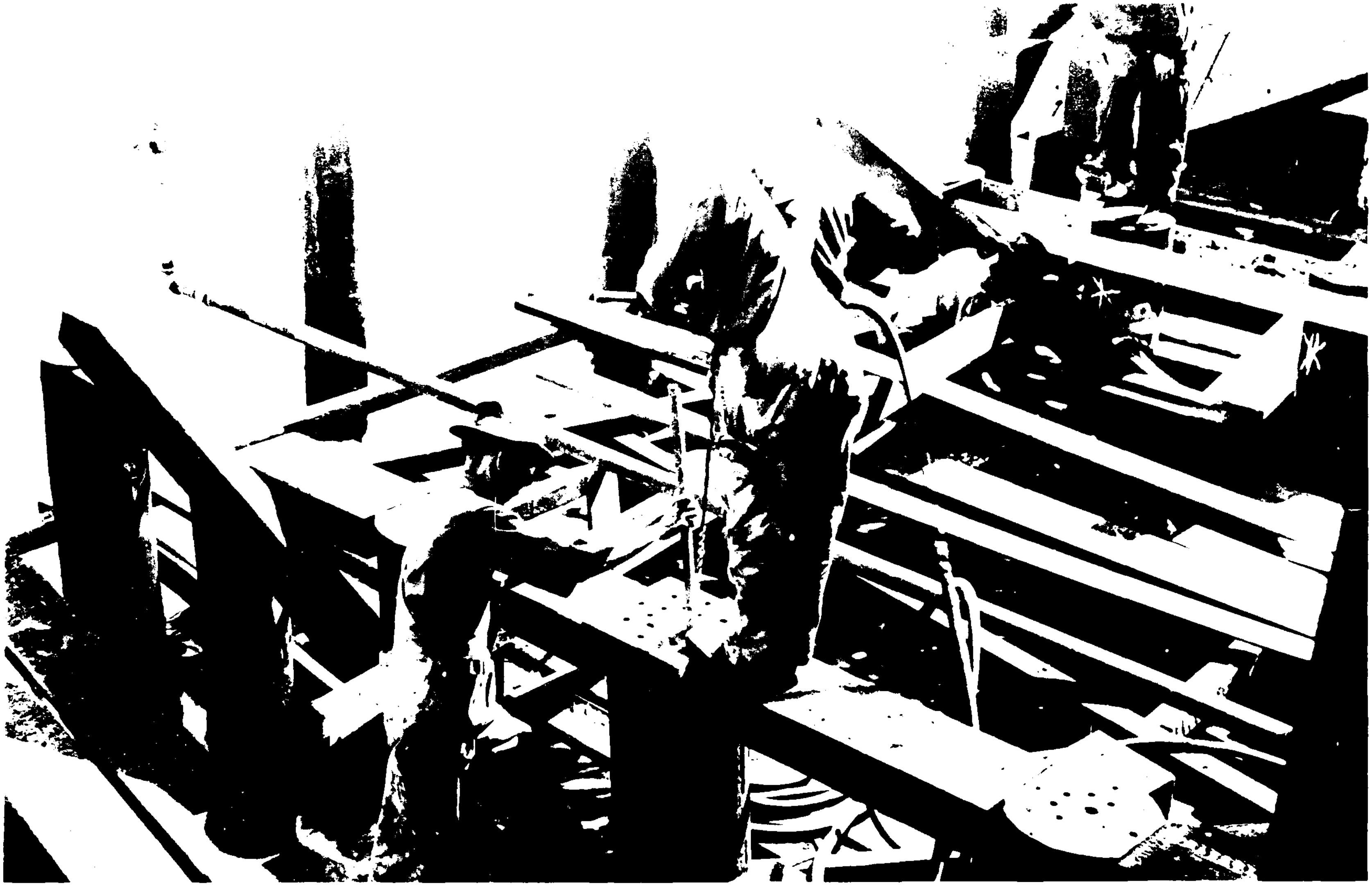


Figure 68. Preparing cutoff piles for coal-tar creosote treatment (photo courtesy of the Port of Los Angeles).

placed on top and covered by a 3.8-millimeter (150 mil) layer of high density polyethylene before placing the pile cap. Side and end grain penetration of the preservative completely impregnates the entire pile top to a depth of more than 25.4 millimeters in less than 2 years.

d. Poles. Prior to World War II, most of the pressure-treated poles used in the United States were treated with American Wood Preservers Association specification grade 1 coal-tar creosote with a specified distillation residue above 355° Celsius of not more than 20 to 25 percent. Coal-tar creosote treatment may still be the preferred preservative under conditions where waterborne preservatives could leach away or cost may be the controlling factor.

In recent years solutions of pentachlorophenol have attracted attention as substitutes for creosote or for use in mixtures with creosote, and large quantities have been used. Thousands of poles have been treated with pentachlorophenol dissolved in the lighter petroleum oils or with solutions containing various proportions of coal-tar creosote and pentachlorophenol dissolved in a petroleum-oil solvent. These poles have not been in service for sufficient time to determine how the results will compare ultimately with those obtained from creosoted poles. Experimental installations under observation, however, are giving excellent results, so that this preservative may find a wide field of use in the future.

Most of the poles that have been pressure-treated and on which the best service records are available are southern yellow pine and coastal Douglas-fir. Preservative retention quantities for these and other species are shown in Table 36. The data are taken from Federal Specification TT-W-571J which gives a more complete specification on the treatment of wood poles.

9. Joining Materials.

a. Metal Connections. The various members and parts of wooden coastal structures are in nearly all cases joined together by metal. Most common are the bolts, spikes, and driftpins which fasten heavy timbers in structures such as groins, jetties, bulkheads, and piers (Fig. 69). Another category includes such items as spike grids and split ring connectors for increasing the shear capacity of bolted joints (Fig. 70), and sheet metal framing anchors for lighter structural framing and miscellaneous hardware such as bearing plates and straps. A third category of metal connection material would include tying items such as rods, wire rope, and chain (Fig. 71). Metal connection material for a timber structure is subject to much the same deteriorating factors in a coastal environment as are metal structures. These are predominantly corrosion and, in some cases, abrasion. They are discussed further in Sections VII and XI.

In addition to resisting corrosion, the material may also have to resist chafing, or abrasion by drifting sand, floating debris, or moored vessels. This factor should be considered in selecting the anticorrosion coating or system, as discussed in Section XI. Because even the best protective system will have only limited life in a severe marine exposure, a program of periodic inspection and preventive maintenance will probably be needed.

Table 36. Preservative retention for treatment of poles (Fed. Spec. TT-W-571J, AWPA C4 and C23 combined).

Preservative	Retention by Species[1] (pcf)				
	Southern Pine[1] Ponderosa[1]	Coastal Douglas Fir[1]	Red Pine[1]	Jack Pine Lodgepole	Western Larch Western Red Cedar Inland Douglas Fir
Coal-tar Creosote[2]	7.5 to 9[3] 12[4]	9 to 12[3]	10.5 to 13.5[3]	12 to 16	16
Pentachlorophenol in heavy petroleum	0.38 to 0.45[3] 0.60[4]	0.45 to 0.60[3]	0.53 to 0.68[3]	0.60 to 0.80	0.80
ACA	0.60[3]	0.60[3]	0.60[3]	0.60	0.60
CCA	0.60[3]	0.60[3]	0.60[3]	0.60	0.60

[1]Retentions are for use as utility poles except for Southern, Ponderosa, and Red Pines and Coastal Douglas Fir which are used for building poles as noted in Footnotes 3 and 4.

[2]According to AWPA C4, creosote coal tar also may be used for utility poles.

[3]According to AWPA C23, the highest retentions are used for building poles as well as utility poles.

[4]Fed. Spec. TT-W-571J requires these high retentions for building poles but not utility poles.

b. Adhesives.

(1) Field Application. At present, the use of adhesives to form or assemble wood structural members is largely confined to factory production of building components. Here the wood parts to be joined can be milled to close tolerances and the joining and curing processes can be closely controlled. For use in a coastal structure where they are exposed to the weather or subject to immersion, a wet-use adhesive, phenol or resorcinol resin or a blend of the two, should be specified for shop-fabricated members. Such members have only limited use in coastal structures, primarily for such items as footbridge girders and trusses, and small-craft docks in marinas.

There is also some use of adhesives in field assembly of wood structural members primarily for buildings. This use is at present largely in secondary connections where a failure would not be hazardous to life or property. The necessary gluing pressure is often provided by nailing. Because in-field gluing and alinement of material may be much less precise than in the shop, it is necessary to use different adhesives, which, until recently, have not

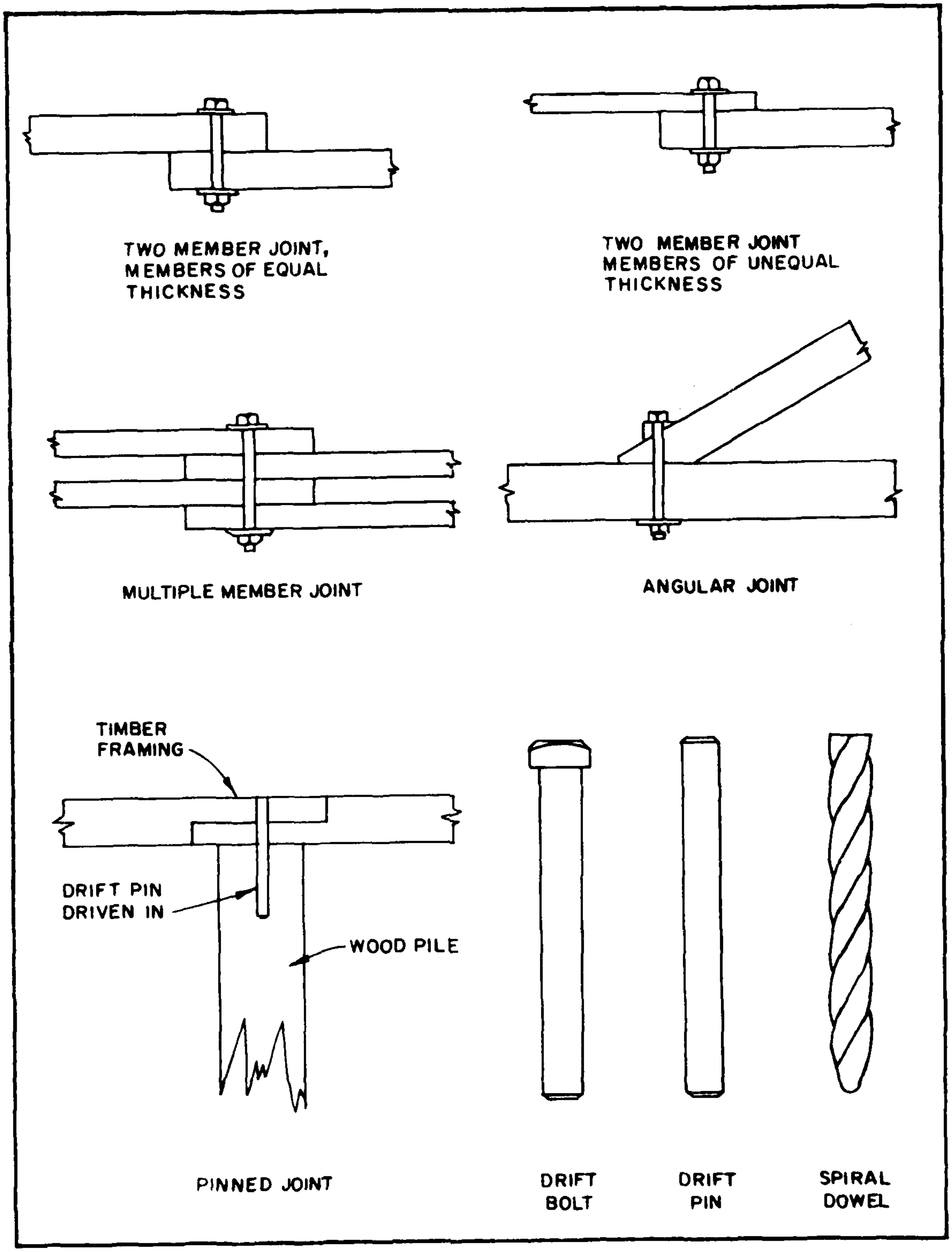


Figure 69. Typical bolted and pinned wood joints.

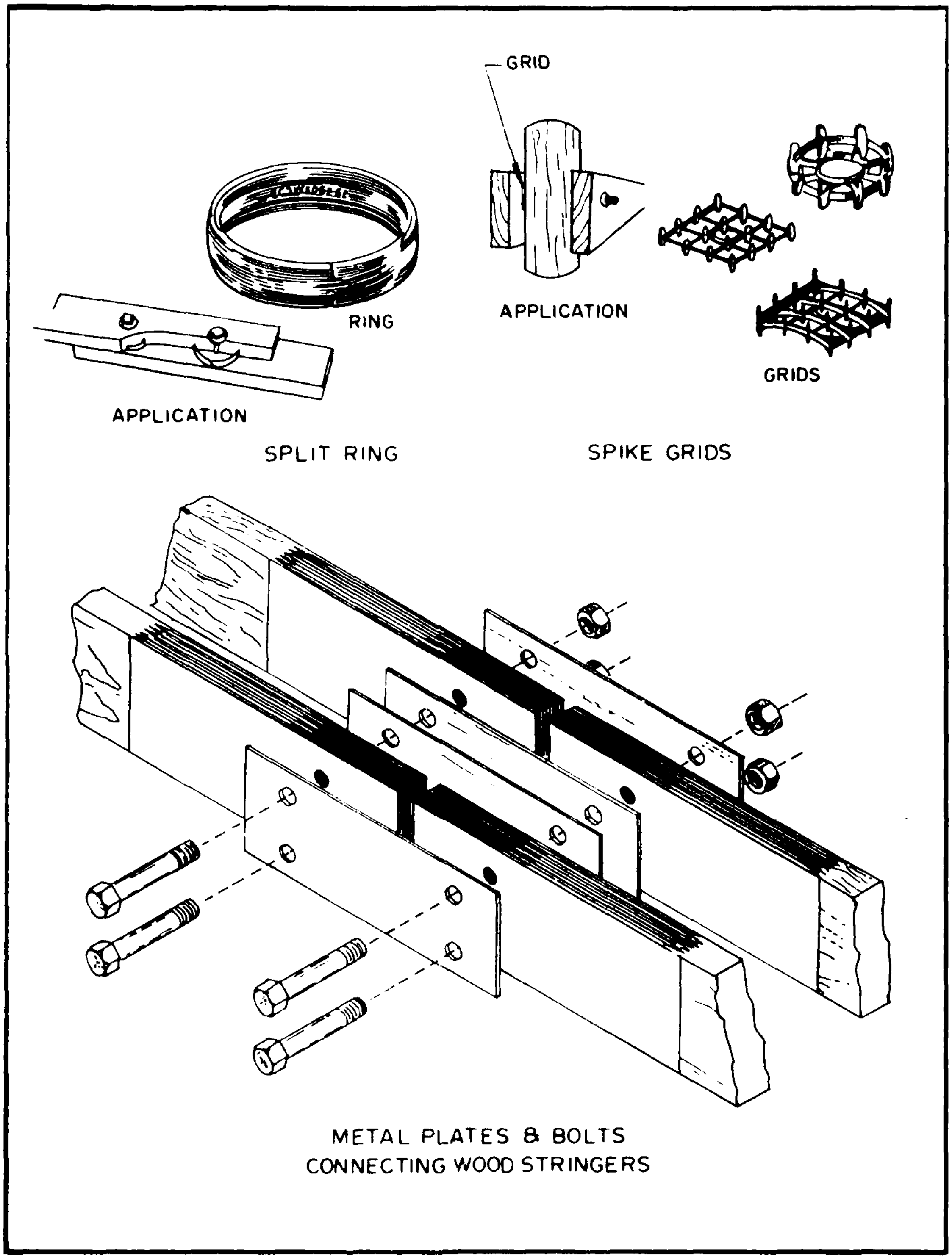


Figure 70. Split rings, spike grids and metal plate connectors.

provided the joint strength and rigidity obtainable in factory gluing. The relatively recent development of fast-curing, gap-filling phenolic and phenol-resorcinol resin adhesives for construction may allow onsite gluing to further expand into the area of primary load-bearing connections {American Institute of Timber Construction (AITC), 1974}.

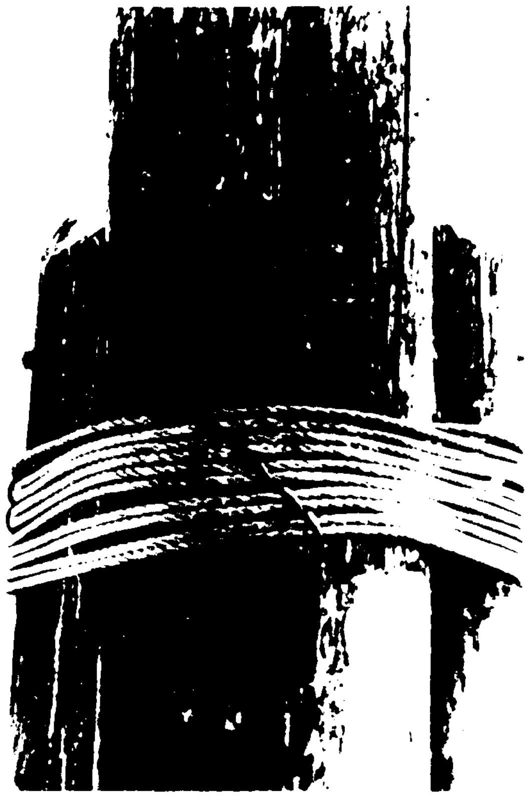


Figure 71. Pile dolphin tied with wire rope.

(2) Shop or Factory Application. Conditions of service determine the type of adhesive required. In general, dry-use (water-resistant) adhesive should be used for interior locations and wet-use (waterproof) adhesive for exterior locations. However, under some conditions, a member glued with dry-use adhesive may be used satisfactorily on an exterior member for certain uses. It is not practical to use both types of adhesives within the length of the same member. If any part of a member's length requires wet-use adhesives, wet-use adhesives must be used throughout its length. It should be kept in mind that the use of a wet-use adhesive will generally increase the cost of a laminated member; therefore, it should not be specified unless actually needed.

(a) Dry-Use Adhesives. Casein adhesive with a suitable mold inhibitor is the standard dry-use adhesive of the structural glued laminated timber industry. It has proved its dependability for over two generations in Europe and North America. It is used in large quantities by other wood products manufacturers as well as this industry. Casein adhesive with mold inhibitor is satisfactory in properly designed, constructed, and maintained buildings as long as the members are not subjected to repeated wettings or high humidity over a long period of time. Although casein adhesives can withstand some wetting during erection of the members, special attention should be given to the protection of the top face of beams, rafters, or arches during shipment and erection when end or beveled faces are exposed at these locations. Angular cuts are often made that pass through one or more laminations and result in feathered ends on the individual laminations. These surfaces have greater than average moisture absorption and should be properly end-sealed to prevent delamination of the feathered ends. Although such damage is not likely to be of structural concern, it may be unsightly. All end cuts should be well sealed (AITC, 1974).

1 Exterior Use. Two major requirements must be met to ensure proper performance of casein adhesives in exterior locations. If the requirements cannot be met, wet-use adhesives shall be used. Complete

protection from the direct effects of precipitation on members must be provided either by undercutting the ends to keep off wind-driven moisture or by the use of fascia boards or end caps to prevent water from collecting on vertical surfaces of the members. Ends of members should be coated with white lead paste or treated with water-repellent sealer before the cap is applied. Casein adhesives are not considered suitable for laminated members intended for exterior use where the moisture content of the wood exceeds 16 percent for repeated or prolonged periods of service.

2 Interior Use. Only one major condition must be satisfied to ensure proper performance of casein adhesives in interior locations: the moisture content of the wood must not exceed 16 percent for repeated or prolonged periods of service.

3 Performance Requirements. Dry-use adhesives shall comply with the requirements of ASTM Standard D3024-72 for structural glued laminated timber.

(b) Wet-Use Adhesives. Phenol, resorcinol, and melamine base adhesives will withstand the most severe conditions of exposure. They are more expensive than water-resistant adhesives. Phenol-resorcinol base or resorcinol base adhesives are the most widely used wet-use adhesives in structural glued laminated members.

1 Use. Although the wet-use adhesives may be employed for all conditions of use, they are generally used only when the equilibrium moisture content of the members in service exceeds 16 percent, such as the following:

(a) Members which must be pressure treated;

(b) marine vessels and structures such as barges, ships, piers, wharves, docks, slips, and dredge spuds; and

(c) structures and members exposed to the weather, such as bridges and bridge girders (other than for temporary construction such as falsework and centering).

2 Performance Requirements. Wet-use adhesives shall comply with the requirements of ASTM Standard D2559-72 for structural glued laminated timber. Only adhesives meeting the requirement for wet use shall be used with California redwood.

10. Repair Materials and Methods.

a. Adhesives. Adhesives are rarely used in field repairs.

b. Concrete Encasements. Wood-bearing piles which have received damage from marine borers (Fig. 72) (either partially or totally destroyed) can be restored to their design capacity, in place, by encasing them in a reinforced concrete jacket. Piles are enclosed with nylon jackets (adding steel reinforcement as necessary) and the jacket is filled with a tremie concrete. A similar successful method is to enclose the damaged part of the pile with a fiberglass form, installing the necessary reinforcing and filling the space between the form and the pile with a hydrophyllic epoxy (Fig. 73).

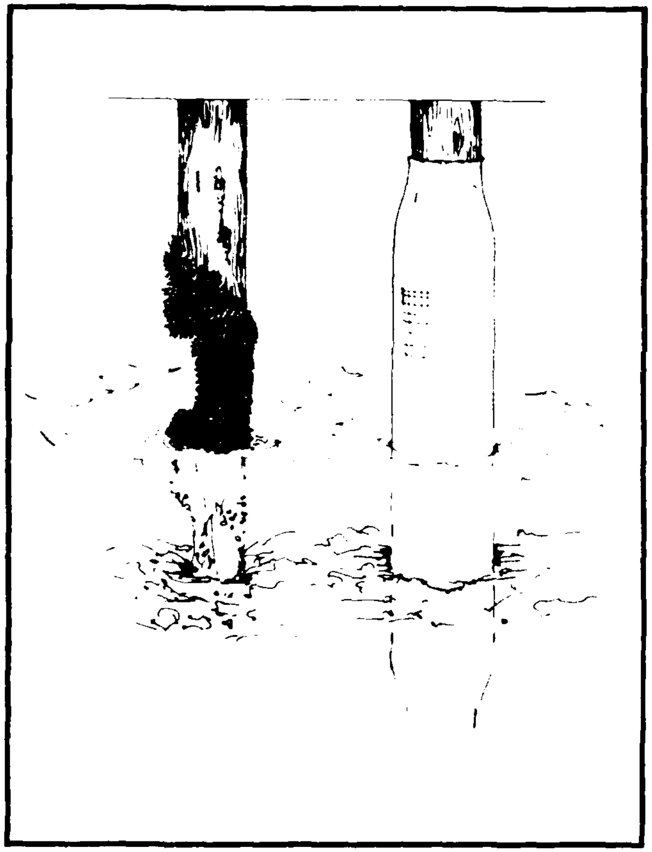


Figure 72. Sketch of typical damaged pile and fiberglass form (U.S. Naval Facilities Engineering Command, 1975).

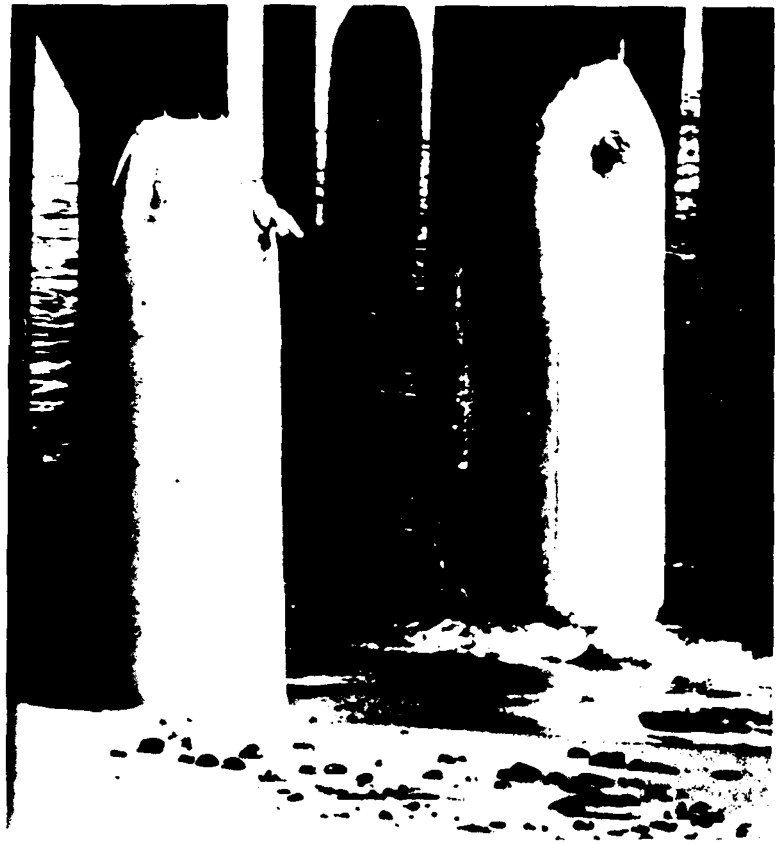


Figure 73. Piles repaired using fiberglass forms and grout (photo courtesy of Aquatic Marine Systems).

Wood pilings that have been severed by marine borers have been successfully restored, in-place, by literally dozens of methods. Most of these are based on external reinforcement, such as heavy wall steel pipe, overlapping the upper and lower pile sections, followed by corrosion protection of the steel by a plastic wrap. Small scale tests in the laboratory have proved the efficiency of these methods in repairing piles, both in the bearing and bending capacity, to achieve their full design loads.

c. Synthetic Materials Wrap. Wood piles can be protected, in place, from marine borer attack, by wrapping with flexible synthetic sheet such as polyvinyl chloride (PVC) or polyethelene sheeting (cigarette fashion) from 305 millimeters (12 inches) below the mud line to 305 millimeters above the highest tide line. In preparing a wood pile for a jacket it is important that all sharp protrusions be removed. In case of barnacles, sharp edges can be smoothed by various simple hand or mechanical devices (Fig. 74).

Modular kits are available which permit fast and positive application from above or below water. This system effectively removes wood piles from their environment. Marine borers attacking the piles while encapsulated under the wraps die from lack of oxygen within 48 hours, while the synthetic sheating prevents further intrusion.

This system has been successfully used on both coasts of the United States, Germany, Australia, the Bahamas, and elsewhere for more than 20 years. The U.S. Navy has also used the system on numerous projects (see NAVFAC specification 75M-B10a).

Other methods of wrapping wood piles with synthetic film before driving have also been tried as shown in Figure 75. Unless the piledriving crew are very careful, the PVC jackets can be ripped during driving. Fortunately, permanent repairs can be made by nailing patches of synthetic film over torn areas with aluminum alloy 5056 roofing nails.

d. In Place Treatment of Timber Cracks. If such cracks make the pile structurally unsound and also expose it to internal marine borer action, the crack can be bolted together with form-fitting steel washers on each side of the pile by one or more bolts. The entire area should then be jacketed with a synthetic film jacket.

e. Replacement. In wood structures, parts such as framing members are frequently repaired by replacement of the damaged member. Replacement is relatively easy because the fasteners are usually in accessible places and the wood members are in discrete sizes of individual pieces. When repairing treated wood, treatment of the new member must be to the same specification as the original. Cuts and bored holes are to be made prior to pressure treatment in the shop when possible. Cut faces of pieces to remain in place must be coated with similar material as the original. New fasteners should be used where there is any damage or corrosion to the original.

Damaged wood piles are removed by pulling, after removing deck and stringers when present. Before pulling, remnants of the damaged pile and

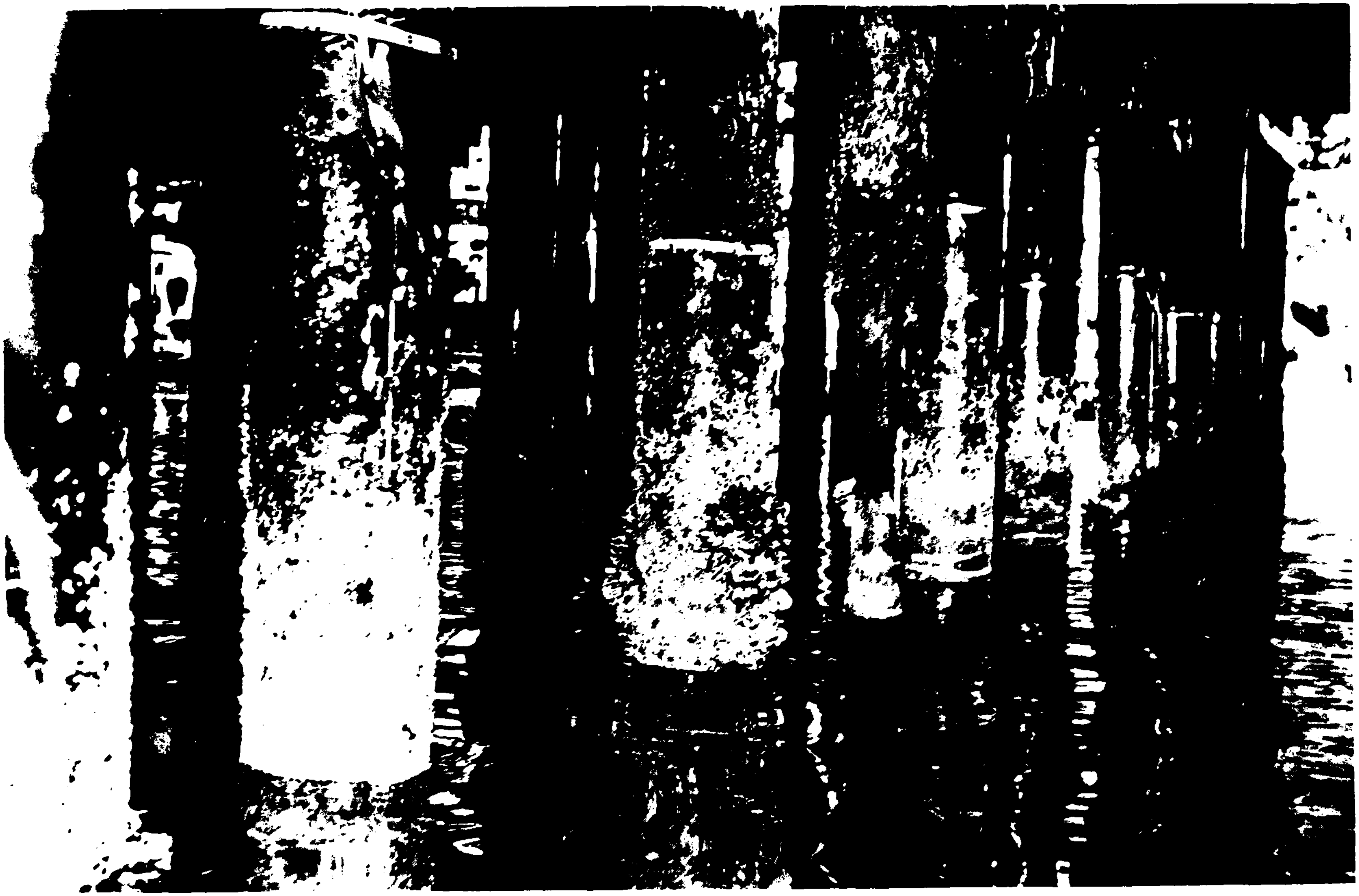


Figure 74. Wood-bearing piles with PVC wrapping (photo courtesy of the Port of Los Angeles).

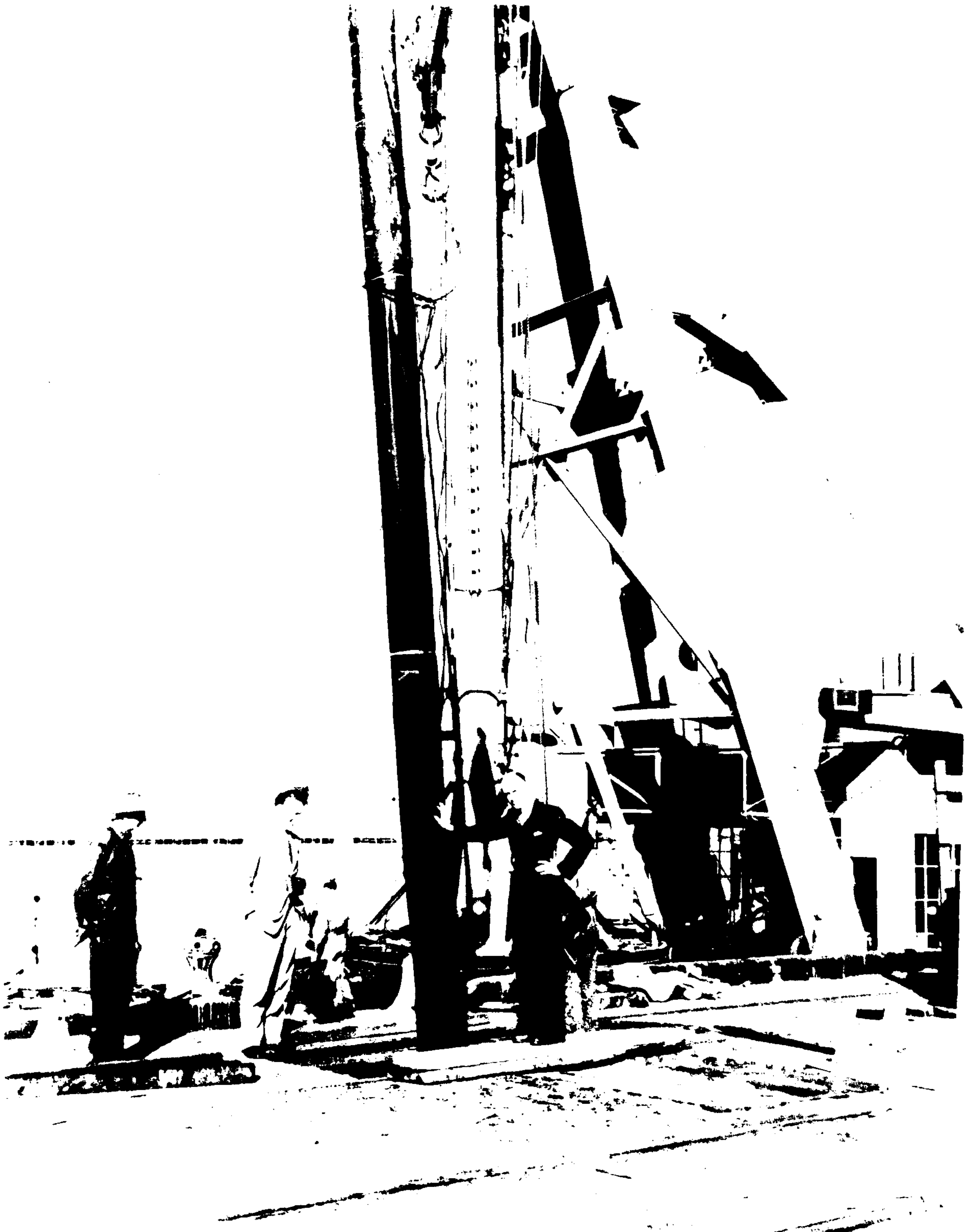


Figure 75. PVC wrapped pile ready for driving (photo courtesy of the Port of Los Angeles).

fastenings must be cleared away to make space for the replacement pile. A replacement pile can then be set in the same hole as the original and driven to refusal. If it is to support a deck, the pile is driven alongside the pile cap, cut off below the pile cap, and pulled over into place. The cut is treated with preservatives and shims are inserted to fill the space between the pile and pile cap. A driftpin is then hammered into place to secure the pile.

11. Environmental Considerations.

a. Chemical Attacks. Chemical actions of three general types may affect the strength of wood. The first causes swelling and the resultant weakening of wood. This action is almost completely reversible when the swelling solution is removed. The second type of action brings about permanent changes in the wood such as hydrolysis of the cellulose by acids or salts. The third action also brings about permanent change in wood and involves delignification of wood and dissolving of hemicellulses by alkalies.

(1) Saltwater and Freshwater. Saltwater and freshwater penetrate the wood fibers. Between zero moisture content and the fiber saturation content (about 30 percent moisture content) wood will swell. The rate of swelling is proportional to the moisture content up to the fiber saturation point. As wet wood dries, the outer part of the wood loses moisture faster than the inner parts thus the shrinkage rate is uneven and can result in the development of checks or cracks. When wood is immersed over extended periods, water can soften the fibers.

Water and particularly saltwater carries dissolved oxygen and marine biota that can severely impact wood or wood fastenings. As a bearer of oxygen, water enhances corrosion of iron and steel fastenings. When wood is periodically wetted and dried in the presence of oxygen it becomes susceptible to fungus which causes dry rot.

(2) Strong Acids. Strong acids (such as nitric and hydrochloric) and highly acidic salts (such as zinc chloride) tend to hydrolyze wood and cause serious strength loss if they are present in sufficiently high concentrations. When the pH of aqueous solutions of weak acids is above 2, the rate of hydrolysis of wood is small and is dependent on the temperature.

(3) Wood Oxidation. Wood oxydation by air in dry locations is slow and attacks the spring wood first to produce a rough or weathered looking surface. Very dry wood can resist hundreds of years of normal exposure to oxidation. Wood can be dissolved by strong acids but basically wood is considered to be somewhat resistant to the action of acids and basic hydroxides. Wood is also resistant to most commercial solvents.

b. Pollutant Attacks. Pollution in both the air and water environments may have the effect of prolonging the useful life of wood by reducing the oxygen supply that oxidizes the wood and supports the biota that attack wood.

c. Sunlight Exposure Effects. Wood in sunlight will expand because of the increase in temperature. In most structures the wood's increase in length for normal rise in temperature is negligible and as a result secondary

stresses due to this change may be neglected. Cut pieces of wood will warp toward the sun unless restrained or dried before use.

d. Wave and Current Effects. Because wood has less strength than some other commonly used structural materials, a larger wood member is needed to adequately protect the wood against the force developed by water currents and waves even where a solid face is presented to the wave and current forces. The resilient characteristic of wood, however, allows wood members to absorb impact energy and rebound intact better than concrete and steel.

e. Effects of Severe Temperature and Ice. Temperature effect upon wood strength is immediate and its magnitude depends on the moisture content of the wood. If the exposure is above normal atmospheric conditions for a limited period and the temperature is not excessive, wood can be expected to recover essentially all its original strength. Air-dry wood can be exposed to temperatures of about 65.6° Celsius (150° Fahrenheit) for a year or more without significant permanent loss of most of its strength properties. Ice or freezing conditions will impact mechanically by causing fiber failure and thus loss of strength through a reduction of section.

f. Marine Organisms. As discussed in subsection 6, Destructive Biota, the principal marine organisms that cause wood destruction in the coastal zone are Teredoes, Limnoria, Poria and Merulius. Most of these animals attack wood as free-swimming organisms. They bore an entrance hole in the wood, attach themselves and grow in size as they bore tunnels into the wood. Wood structures are protected from these animals by proper treating with creosote or coal-tar solutions or by a protective enclosure.

g. Periodic Wetting and Drying. Wood in a marine environment should always be protected from excessive moisture or water and therefore has little change in its structural or mechanical properties. If the preservatives eventually leach out of the wood cells, then alternate expansion and contraction of the wood cells can result in gradual and slow deterioration. Wood structures have a history of long service life even when subjected to alternate wetting and drying.

h. Wind Erosion. Wood being a relatively soft construction material as compared to concrete or metal, it can be eroded by wind action. Wind does not erode wood directly but strong winds picking up particles of sand or other materials will cause a wood surface to wear. Erosion of this kind will usually take place near the ground line.

i. Effects of Burrowing Animals. Marine animals will burrow into wood very rapidly unless the wood is protected by appropriate preservatives. Wood is sufficiently soft as to offer little resistance to burrowing attack and in addition serves as a food source to the animals. Onshore termites are very destructive to wood. These attacks, if left unchecked, will result eventually in the loss of all structural properties of wood.

j. Effects of Flora. There are no reported effects of flora growth on wood.

k. Fire. Wood, when exposed to fire, forms a self-insulating surface layer of char and thus provides a degree of its own fire protection.

Although the surface chars, the undamaged wood below the char retains its strength. Heavy timber members will retain their structural integrity throughout long periods of fire exposure because of their size and the slow rate at which charing penetrates inward from the wood surface.

l. Abrasion. In the coastal environment, abrasion of wood occurs from sources such as scour by wind- and water-driven sand as well as the working or rubbing at joints in the wood structure. Abrasion can be from beneficial use as from vehicle traffic on a pier or from rubbing of floats on anchor piles. The wearing away of a wood structure in this manner will eventually reduce the structural integrity of the structure.

m. Seismic Effects. Seismic activity can have a significant effect and in some locations a devastating effect. Ground shaking can stress structures to overload and cause destruction. Natural alluvial terraces or manmade landfills in the coastal zone are subject to liquefaction during severe earthquakes which cause the ground to slump and flow horizontally. Structures founded on such terraces in a severe seismic area are subject to destruction if liquefaction occurs. However, under less severe conditions, wood performs very well in seismic events because of its resiliency. This characteristic of wood allows it to flex during ground shaking and reduce the stresses that might destroy structures of more rigid materials.

n. Human Activity. Human use of wood structures can eventually cause the wood to wear out; the worn wood parts could be replaced or the whole structure could be abandoned. On wharves and piers ship moorings wear or break fender piles and vehicular traffic on the deck wears out the surface timbers. Human use engenders risks in the form of explosions, fires, and accidental impact loads, all of which can destroy wood members of coastal structures. Vandalism can cause serious damage to wood: some wood may be sacrificed for firewood; wood may be destroyed by the target practice of shooters; and amateur wood carvers may cause deterioration.

12. Uses of Wood In Coastal Construction.

a. General.

(1) Dimension Lumber. Untreated dimension lumber can be used in temporary situations during the construction phase of a project or where the life of the wood is to be less than a few months. It can also be used in any situations where the wood can be protected either by a covering, for example interior framing of a building, or where it is to be painted and maintained in a painted state for the projected life of the installation. Untreated dimension lumber should not be used in direct contact with the ground or sea water. Untreated dimension lumber is used in form work for concrete. It is also used in a variety of ways such as for dunnage or machinery supports.

Foundations and sill plates for frame buildings are usually pressure treated with chromated copper arsenate. Any use where contact with the earth exposes the lumber to rot, fungus, or insect attack requires treatment to obtain a satisfactory useful life. Specific treatment would be determined by the conditions of service. Exposed uses subject to severe weathering or prolonged (or periodic) immersion in seawater should be pressure treated

with coal-tar creosote; otherwise, one of the other treatments could be satisfactory.

(2) Piles and Poles. Wood piles and poles used in the coastal environment are nearly all pressure treated with coal-tar creosote to resist insect attack or, in water, marine borers and limnoria. Properly treated piles and poles will also withstand rot and fungus attacks. Piles are used for building foundations, support for piers, wharves, trestles, jetties, groins, and bulkheads. Also, they are used in fender systems along the wharves and to anchor floating moorings for small boats.

It is unlikely that untreated piles or poles would be used in the coastal environment except for temporary uses during construction for false work or to carry electric power and telephone lines to the construction site.

(3) Beams and Stringers. Lumber classified as beams and stringers (having 5 inches (125 millimeters) as their least dimension) are seldom used untreated in the coastal environment. The principal use would be in protected space as framing for buildings or covered structures where the covering or painting provides sufficient protection.

Coal-tar creosote treated beams and stringers are used extensively in the coastal environment.

(4) Glued and Laminated Wood.

(a) Plywood. Dry-use plywood is seldom used in the coastal environment because of its extreme susceptibility to the generally high humidity. Any use would have to be very temporary or very well protected from the prevailing moisture.

Wet-use plywood has many applications in the coastal environment. Diaphragms in buildings, roofs, walls, and floors are regularly sheathed with wet-use plywood. Plywood is sometimes used for gussets in wood frames to join the members. Plywood is used extensively in making forms for concrete work. Signboards are frequently made of plywood. Covers, such as for pits and valve boxes, can be made of plywood where traffic is light or in nontraffic areas. Wet-use plywood can be further treated with preservatives to extend its useful life in extreme environments, such as immersion in seawater.

(b) Laminated Wood. Wood in this category is what is generally referred to as "glue-lam," or more properly glued laminated wood. Because of its better quality control, strength, and capability of being sized to suit the need, it can be the preferred material for many applications where columns, post , beams and girders are used. In the coastal environment, wet-use glue is absolutely essential and glue-lam members must have preservative treatment in any use where other wood forms would require it.

(5) Miscellaneous Wood Forms. Although most people think of finished lumber and timbers cut to rectangular sizes from large trees or of piles peeled and trimmed when they think of wood, there are other useful forms of wood that can be used in the coastal zone. Small branches, saplings,

brush, cane, bamboo, and reeds have all been used to make devices to control water currents, stabilize bottom sediments or to control dry sand buildup. Where these wood forms are indigenous to the area or readily available they can be valuable materials.

b. Offshore Structures.

(1) Breakwaters and Caissons. Wood is seldom used in offshore structures of this type but dimension lumber and wet use plywood may be used for navigation aids or other incidental small structures that may be mounted on offshore breakwaters and caissons.

(2) Pile Dolphins. Wood is frequently used offshore for pile dolphins and other mooring or anchorage devices such as guide piles for floats or piles for channel markers. Pile dolphins are clusters of wood piles tied together as in Figure 71.

(3) Floats. Wood is used extensively in the construction of floating structures. Although the tendency is toward synthetic materials for small flotation devices, wood remains the most used material for framing flotation units and providing a platform for access and mooring fastenings. Wood flotation units such as logs could be used to form floats or booms for the containment of surface debris.

c. Shore-Connected Structures.

(1) Breakwaters and Jetties. Wood uses in shore-connected breakwaters and jetties would be the same as described for offshore structures.

(2) Groins. Wood is frequently used in the construction of groins. Wakefield sheet piles are commonly seen used as shown in Figure 61. The sheet piles are secured with timber wales at the top. Wood planks spanning between wood piles create another type of groin structure as seen in Figure 76.

(3) Bulkheads. Wood bulkheads are usually one of two kinds. Wakefield sheet piles are driven along the bulkhead line and tied back to the embankment by timber wales and tie rods to imbedded anchors (deadmen). Otherwise, vertical piles acting as soldier beams are driven at regular intervals along the bulkhead line and wood planks are placed to span horizontally between them. Piles can be tied back to deadmen.

(4) Revetments.

(a) Pile Revetment. Slopes can be stabilized using parallel piles laid along the slope as shown in Figure 77. Piles used this way must be securely tied to headers or staked down.

(b) Fascine Mattresses. The word "fascine" comes from the Latin "fascina" meaning a bundle of sticks. Fascine mattresses are used as submerged scour aprons and as filter blankets along revetments. There are many ways to construct the blankets but they basically all consist of sticks tied together in bundles and arranged in mattresses about 20 meters (62 feet) wide and up to 200 meters (620 feet) long. The mattresses are

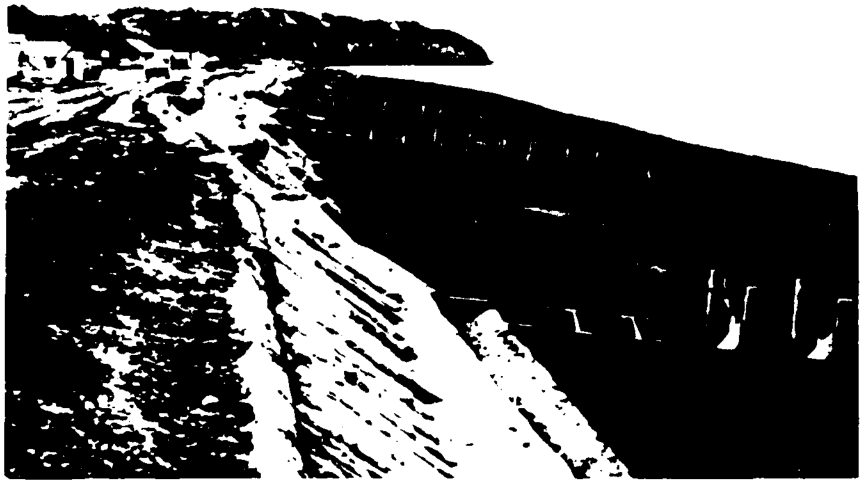


Figure 76. Beach protection with "billboard" groins, Ninilchik Harbor, Alaska.

Figure 77. Piles laid on slope to prevent beach erosion, Ninilchik Harbor, Alaska.

brush, cane, bamboo, and reeds have all been used to make devices to control water currents, stabilize bottom sediments or to control dry sand buildup. Where these wood forms are indigenous to the area or readily available they can be valuable materials.

b. Offshore Structures.

(1) Breakwaters and Caissons. Wood is seldom used in offshore structures of this type but dimension lumber and wet use plywood may be used for navigation aids or other incidental small structures that may be mounted on offshore breakwaters and caissons.

(2) Pile Dolphins. Wood is frequertly used offshore for pile dolphins and other mooring or anchorage devices such as guide piles for floats or piles for channel markers. Pile dolphins are clusters of wood piles tied together as in Figure 71.

(3) Floats. Wood is used extensively in the construction of floating structures. Although the tendency is toward synthetic materials for small flotation devices, wood remains the most used material for framing flotation units and providing a platform for access and mooring fastenings. Wood flotation units such as logs could be used to form floats or booms for the containment of surface debris.

c. Shore-Connected Structures.

(1) Breakwaters and Jetties. Wood uses in shore-connected breakwaters and jetties would be the same as described for offshore structures.

(2) Groins. Wood is frequently used in the construction of groins. Wakefield sheet piles are commonly seen used as shown in Figure 61. The sheet piles are secured with timber wales at the top. Wood planks spanning between wood piles create another type of groin structure as seen in Figure 76.

(3) Bulkheads. Wood bulkheads are usually one of two kinds. Wakefield sheet piles are driven along the bulkhead line and tied back to the embankment by timber wales and tie rods to imbedded anchors (deadmen). Otherwise, vertical piles acting as soldier beams are driven at regular intervals along the bulkhead line and wood planks are placed to span horizontally between them. Piles can be tied back to deadmen.

(4) Revetments.

(a) Pile Revetment. Slopes can be stabilized using parallel piles laid along the slope as shown in Figure 77. Piles used this way must be securely tied to headers or staked down.

(b) Fascine Mattresses. The word "fascine" comes from the Latin "fascina" meaning a bundle of sticks. Fascine mattresses are used as submerged scour aprons and as filter blankets along revetments. There are many ways to construct the blankets but they basically all consist of sticks tied together in bundles and arranged in mattresses about 20 meters (62 feet) wide and up to 200 meters (620 feet) long. The mattresses are

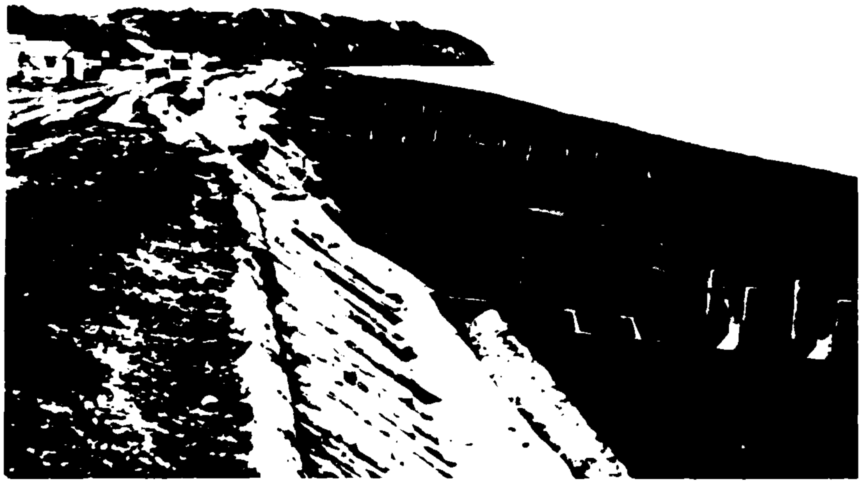


Figure 76. Beach protection with "billboard" groins, Ninilchik Harbor, Alaska.

Figure 77. Piles laid on slope to prevent beach erosion, Ninilchik Harbor, Alaska.

made in a place that is normally dry but can be flooded (either at high tide or by removing a gate) for towing the mattress to its final location. The mattress is then loaded with stones and sunk into place. It is then covered with stones as needed to resist the expected currents. Examples of fascine mattresses are shown in Figure 78. Finer material is placed on the bottom of the mattress where it contacts the sand and coarser material is on top to support the stones. These mattresses will deteriorate rapidly if left where they would receive periodic wetting. Therefore, they will only work where they are completely submerged all the time. Where damage by marine borers is expected, preservative treatment could be applied but the cost of treatment may indicate that some other material be used (Van Bendegon and Zanen, 1960).

(5) Submerged Screens. Submerged screens for current control can be made of "wattles" (flexible branches woven around posts) as shown in Figure 79 or can be made by combining stones and small poles (or bamboo) into cribs. The cribs are formed by forming a lattice work of poles to form a cage (crib) and filling it with stones for stability. Figure 80 shows some crib types.

(6) Piers and Wharves. Piers and wharves may be made entirely of wood construction with incidental use of metal fastenings and rock for slope protection. Piles, pile caps, stringers and decking would all be treated and placed as discussed in earlier paragraphs of this section. These wood members can also be used in conjunction with other materials, such as concrete piles.

Mooring dolphins and fender piles for piers and wharves are frequently made of wood to take advantage of the energy absorbing property of wood even when the remainder of the structure is of some other material such as concrete.

(7) Sand Fences. Fences made of brush have proved more effective than fences made of boards in building sand dunes on the Outer Banks of North Carolina (Savage, 1963). In this installation, brush was held upright between pairs of wood plank rails as shown in Figure 81. The filtering action of the brush apparently trapped more sand than the wind deflection action of wood slats.

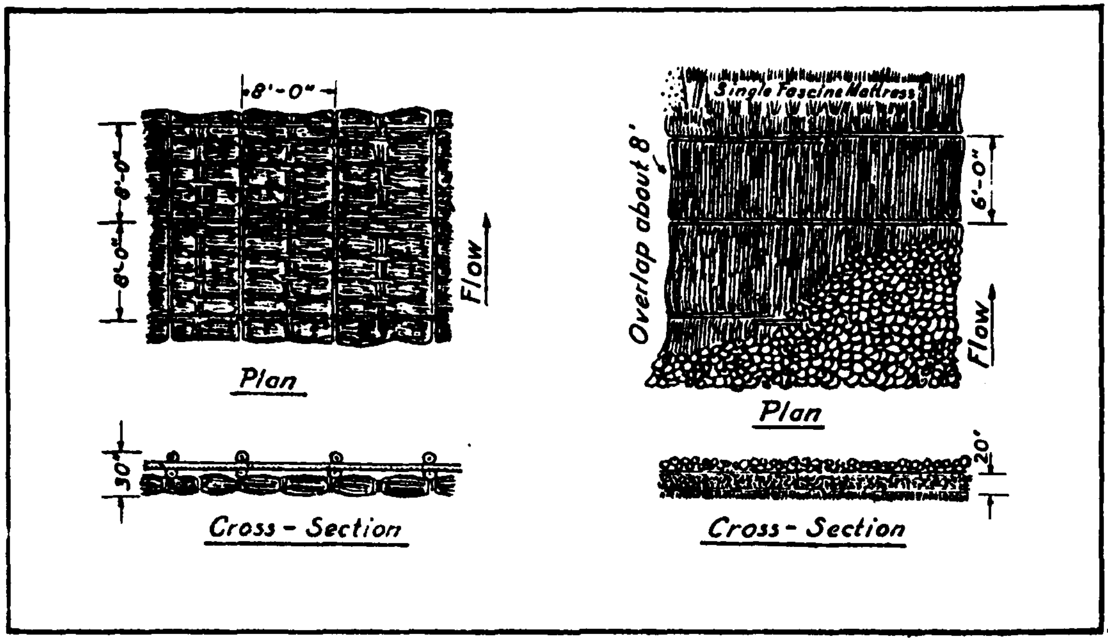


Figure 78. Two methods of making fascine mattresses (Van Bendegon and Zanen, 1960).

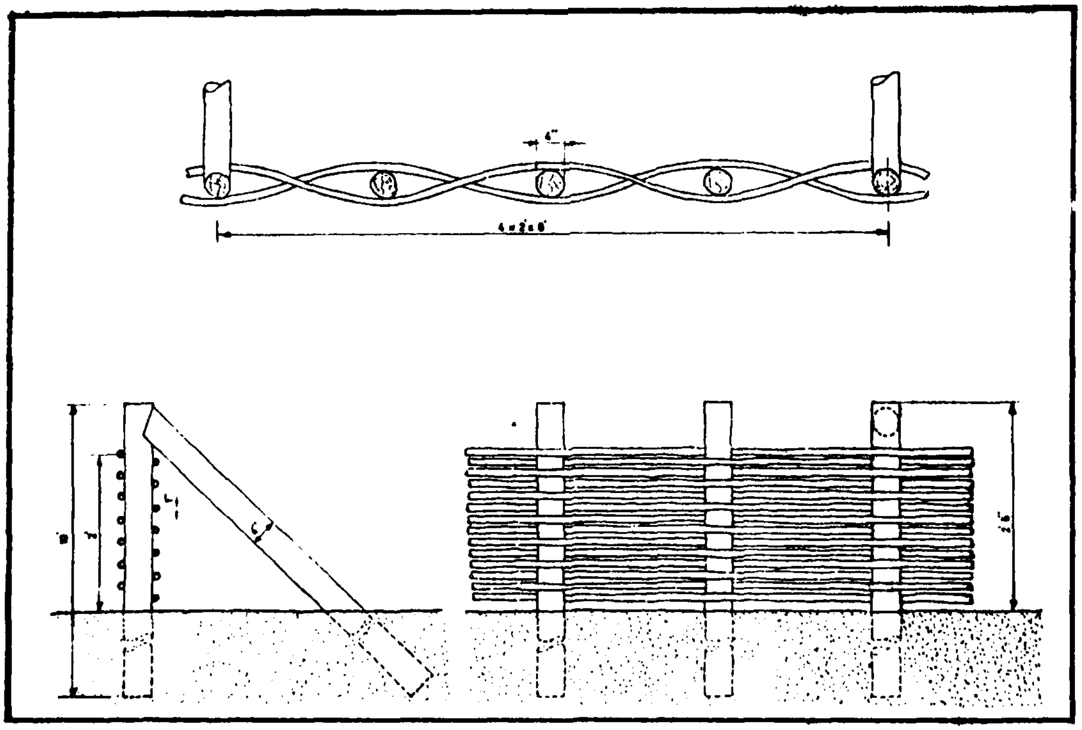


Figure 79. Submerged current control screen made of "wattles" (NEDECO, 1959).

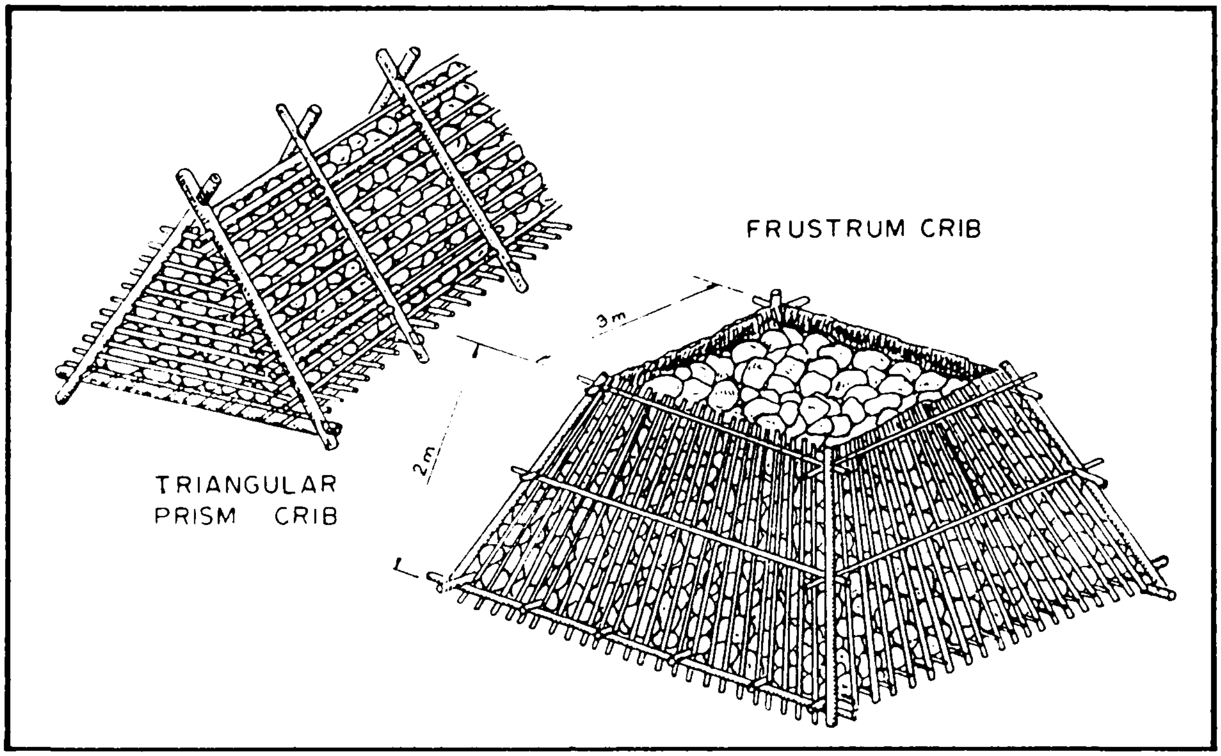


Figure 80. Examples of wood-formed cribs (Van Bendegon and Zanen, 1960).

Figure 81. Sand fence using brush for filter material (Savage, 1963).

IX. PLASTICS

1. General.

a. Chemical and Manufacturing Properties. Chemically the term "plastics" is applied to a large group of synthetic materials that are processed by molding or forming into a final shape. Plastics are composed of chainlike molecules of high molecular weight, called polymers, that have usually been built up from simpler monomers.

All plastics share many common properties and, in general, have four things in common. First, at some stage in their production they are soft and pliable and can be formed, by the application of heat, pressure or both, into definite desired shapes. Second, plastics are organic materials; i.e., they are based on a carbon structure. This distinguishes them from such materials as metals, ceramics, and concrete. Third, plastics are synthetic materials and are products of chemical processes that alter the characteristics of the raw materials from which they derive. Fourth, plastics are high polymers; they consist of monomer atoms joined together into molecular aggregations.

Different monomers are used to manufacture each different type or family of plastics. Each plastic has a particular combination of properties, processing requirements, and economics that make it ideally suited for certain applications, yet unsuitable for many others.

b. Thermoplastics and Thermosets. Plastics in general may be classified into distinct groups. These are thermoplastics and thermosetting plastics or thermosets. Thermoplastics soften repeatedly when heated and harden when cooled. At high temperatures they may melt and at low temperatures become brittle. The process of heating and softening and cooling and hardening may be repeated indefinitely for plastics such as polyethylene, polyvinyl chloride, acrylics, nylon or polystyrene. Thermosetting plastics go through a soft plastic stage only once. When hardened, an irreversible change takes place and they cannot be softened again by reheating. Some thermosetting plastics are polyesters, epoxies, phenol-formaldehydes, melamine-formaldehydes and silicones.

c. Copolymers and Composites. Plastics can be combined like metal alloys to attain the best qualities for a particular end use by selectively drawing from the best attributes of the blended components of the polymers. The process is referred to as copolymerization and the products are called copolymers. Plastics used for structures, including those used in the coastal zone, are most commonly composites or copolymers rather than pure forms. Reinforced plastics are one category of composites in which the plastic is strengthened and stiffened by combining it with high strength fibers such as glass. Sandwich-type plastics contain a variety of strong, thin facings and lightweight cores. There are also the polymer concretes, which contain plastic matrix in place of or in addition to inorganic cement.

d. Structural Properties from Additives. Because all plastics are synthetic, during their production various things can be done to alter their characteristics by the introduction of additives. These include

plasticizers, fillers, colorants, stabilizers, and impact modifiers. Plastics which are hard and rigid or brittle at normal temperatures can be made pliable and flexible by the addition of plasticizers.

Fillers are normally added to both thermoplastics and thermosets to enhance their processing, performance, or economics. For example phenolics, without the addition of fillers, are hard and brittle, shrink in molds and may crack. The addition of finely ground wood flour makes it easier to mold and less costly. Powdered mica will enhance electrical resistance while the addition of asbestos will improve heat resistance. Impact resistance can be improved by the addition of chopped fibers such as natural fibers, tire cord, rayon or glass. Colorants are easily added to plastics although they are not usually necessary in coastal structures.

Stabilizers are an important group of additive materials used to increase the resistance of plastics to deteriorating influences of weather, ultraviolet light, or radiation. Most plastics in their pure form do not have a great deal of resistance to these environments. The addition of stabilizers retards thermodegradation and oxidation. Materials with these kinds of additives, in outdoor exposures, may have a design life of 30 to 40 years.

Another important category of additives are the impact modifiers. The inclusion of various fillers or plasticizers will increase the impact resistance of plastics which are normally very brittle.

e. Durability Properties. In addition to structural qualities, plastics possess other desireable characteristics as a construction material. They are easily formed, corrosion resistant, lightweight, wear resistant, energy absorbent, impact resistant, flexible and ductile, and are used for insulation due to their thermal and electrical resistance. Energy absorption and impact resistance vary with the different plastics. Rubber, being a synthetic and not usually considered a plastic, can be formulated to have a high degree of impact resistance within a large range of stiffness characteristics.

Fire is a necessary consideration in the selection of all structural materials. Plastics will burn or disintegrate if exposed to fire or high temperatures. Some will burn easily, some slowly, others with great difficulty. Some will not support combustion in the absence of flame. Improved fire resistance can be achieved by incorporating flame-retardant chemicals into the molecular structure of the plastic materials. Phosphorus and halogens have been effectively used for this purpose.

2. Geotextile Filters.

a. General. Because the most common use of plastics or geotextiles in coastal construction is as a filter, that use is the predominant topic of this section. These filters have been known as filter fabrics, construction fabrics, plastic filter cloth, geotechnical fabrics, and engineering fabrics. ASTM Joint Subcommittee D-18.19/D-13.61 is developing test procedures for evaluating these fabrics and has adopted the name of "geotextiles." Geotextiles are used in engineering as filters, materials separators, and reinforcement for soils. These fabrics may be used in coastal structures to

perform one or more of these roles, however; they are most frequently used as filters which permit the passage of water through the fabric but not soil or sand particles. Geotextiles used as materials separators prevent the mixing of materials that should remain apart such as poor subgrade soil and good subgrade gravel. Geotextiles have also been successfully used as reinforcing in the paving of roads and to restrain lateral movements of embankments built on soft soils. Koerner and Welsh (1980) give design guidance for many uses.

The use of geotextiles has expanded rapidly in the past 20 years and many different kinds are available today. However, there are constraints that must be removed before geotextiles achieve unqualified acceptance. One of these is lack of standardization. Many fabrics are made by suppliers in different ways, out of different materials, and for different uses. In choosing a fabric for a project, it may be necessary to consider tensile, elongation, and puncture properties, plus factors such as fabric elasticity, porosity, permeability, and resistance to abrasion, chemicals, light, weather, and temperature as well as resistance to biological attack.

Because geotextiles have many different uses in coastal structures, drainage ditches, riverbank protection, and subgrade construction, no one fabric is right for all applications. It remains to be determined just what properties are important for each end use and what range of values for each property is sufficient. However, based on the successful use of many geotextile filters over the past 20 years, the promise of longevity is exceedingly favorable. A prospective geotextile user should obtain advice and information from engineers experienced in their use as well as from more than one supplier.

The term geotextile filter as used in this report refers to a permeable fabric constructed of synthetic fibers designed to prevent piping (prevent soil from passing through it) and remain permeable to water without significant head loss or without permitting the development of excessive hydrostatic pressure.

b. Design Properties. A geotextile filter must be sufficiently permeable to relieve the hydrostatic pressure differential between its sides by allowing the passage of ground waterflow without detrimental head loss, and it must prevent the passage, or piping, of adjacent granular or fine soil. A geotextile is used to replace all or part of a conventional filter system consisting of one or more layers of granular material. Figure 82 illustrates a geotextile replacing a layer of gravel beneath a revetment, showing how the filter is designed to prevent protected soil from being washed through the overlying armor. It also demonstrates how a geotextile can be incorporated into a toe protection apron. To be effective, the geotextile must be designed to suit the grain size, ground water, and wave conditions of each specific site as well as the type of structure in which it is to be included.

In order to function satisfactorily, the geotextile filter must have the physical durability and filtering integrity to perform consistently throughout the design life of the structure. Durability depends on the chemical composition of the fibers, construction of the fabric, and physical properties of the fabric in its completed (finished) form. To ensure durability, specifications for fabric should describe the basic chemical

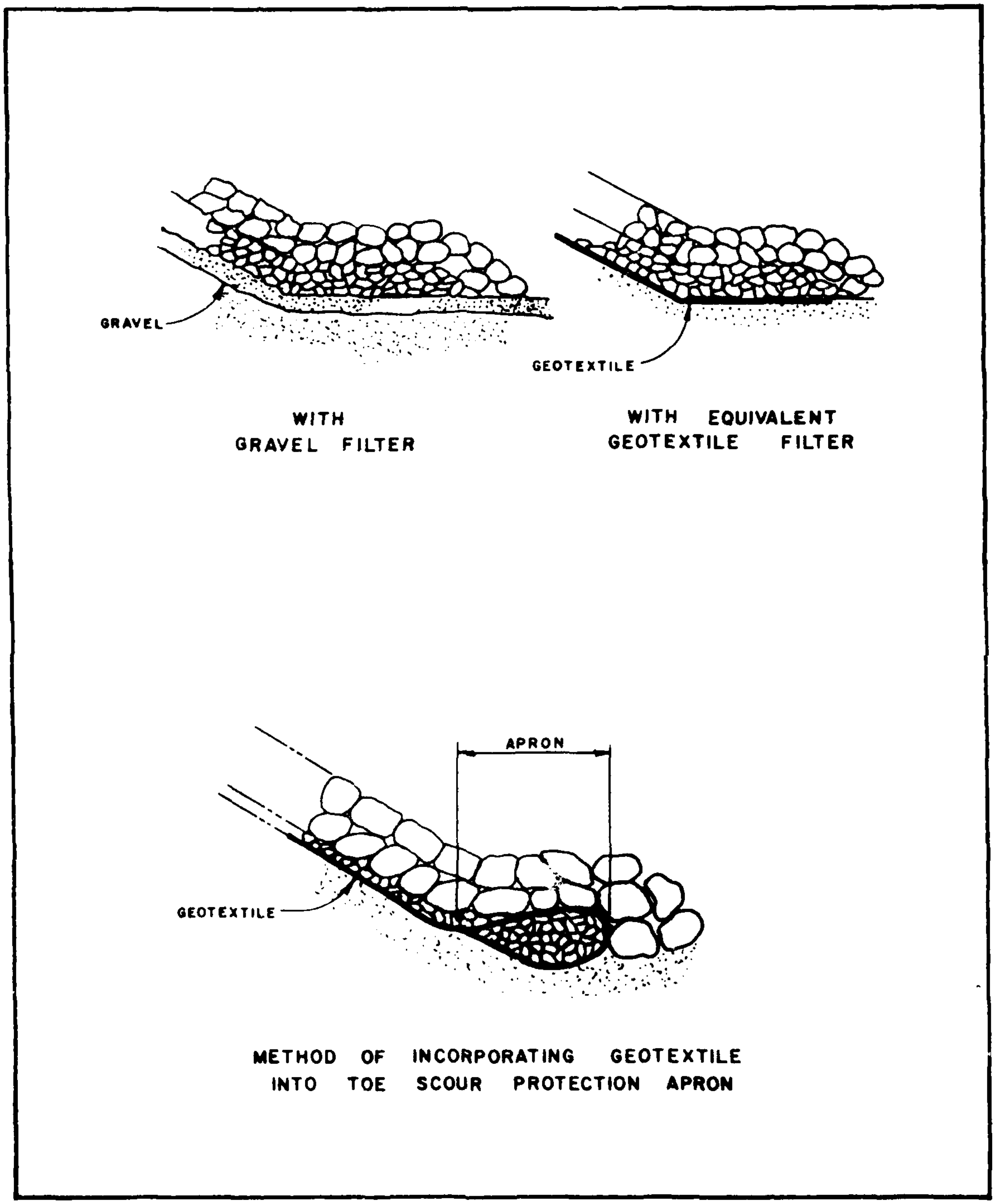


Figure 82. Geotextile filters in revetments.

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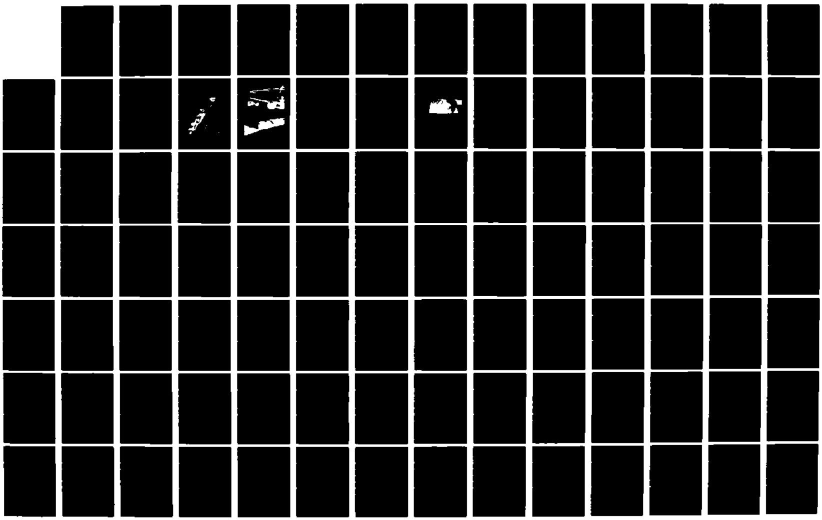

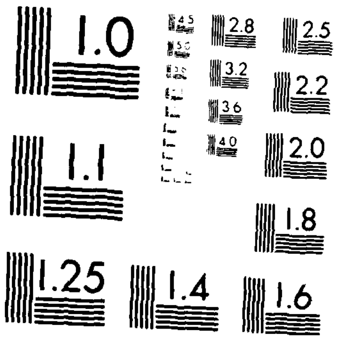
1.0
1.1
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3.2
3.6
4.0

composition, fabric construction, and additives. The 1977 Chief of Engineers Civil Works Construction Guide Specification CW 02215 (U.S. Army Corps of Engineers 1977) states that "The plastic yarn shall consist of a long-chain synthetic polymer composed of at least 85 percent by weight of propylene, ethylene, ester, amide or vinylidene chloride." All geotextiles for coastal applications must meet this requirement. Filtering integrity depends on the fabric's ability to resist piping through the fabric and clogging. These properties are discussed in subparagraph c below. These topics are covered in subparagraphs 2c(1) and 2c(2). Filtering integrity also depends on the fabric's resistance to loss of permeability due to distortion of the pores by elongation of the fibers under stress, a physical property of the fabric, or by melting in fire.

(1) Chemical Stability and Resistance. The first extensive research and testing of geotextiles for filters was by Calhoun during the period 1969 to 1972 (Calhoun, 1972). In the course of his investigations, tests were conducted to determine the chemical stability and resistance of three types of synthetic polymers, polyvinylidene chloride, polypropylene and polyethylene. Further research by Bell and Hicks (1980) also investigated chemical properties of these three polymers plus polyester and polyamide. The results of these testing programs established the fact that these synthetics have high chemical stability and resistance to chemical attack (acids and alkalies), and can be used in conventional soil applications with confidence. If the fabric is to be used in an environment containing petroleum products, it is recommended that the geotextile's resistance to these materials also be determined.

(2) Fabric Construction. Selection of a geotextile for a filter should be based on the filtering and physical properties as well as the chemical properties of the fabric consistent with the site-specific requirements. Bell and Hicks (1980) found that most fabric engineering properties are more strongly influenced by the fabric construction than the polymer. One of the most extensive and thorough fabric strength testing studies, involving 27 commercially available fabrics, was performed for the Army Engineer District, Mobile, by Haliburton, Anglin, and Lawmaster (1978). It was concluded that fabric construction had more influence than the type of synthetic fiber in the fabric. Because fabric construction is the predominant factor affecting physical properties and filtering performance, three general types of fabric construction are discussed: woven, nonwoven and combination fabrics.

(a) Woven Fabrics. As the term implies, woven fabrics (commonly called cloths) are manufactured by weaving. Normally, the yarns cross at right angles, overlapped one over the other. The longer direction of the cloth, when it is being woven, is called the warp or machine direction. The narrower direction is referred to as the fill or cross-machine direction. In geotextiles, normally the warp direction is stronger than the fill, although the cloth may be produced with equal strength in both directions or a stronger fill than warp. Filters are woven using a variety of yarns discussed below.

1 Monofilament Yarns. Monofilament yarns are a single filament of a polymer, which prohibits absorption of water by the yarn. This was the only type of geotextile used in coastal structures in the United States from 1958 to the mid 1970's. Fabrics woven of monofilament

yarns have relatively regular and uniform pore sizes. "Some engineers believe that because of their simple pore structure, the monofilament fabrics are more reliable filter materials and use them in critical installation, where their higher cost can be justified" (Bell and Hicks, 1980). The fabric is thin.

2 Multifilament Cloths. Multifilament cloths are woven of yarns containing many fine filaments, except fibrillated yarns which are produced from synthetic sheets. Fibrillated yarns are formed of fibers from sheet plastic film. All multifilament fabric can be produced with higher tensile strengths than monofilaments. With the exception of fibrillated fabrics, multifilament cloths also have a simple, relatively regular and uniform pore size, and generally are thin. Fibrillated fabrics have a slightly more irregular pore system and generally are thicker.

3 Mono-Multifilament Combination Fabrics. Mono-multifilament combination fabrics contain monofilament yarn in one direction and multifilament in the other. The pore sizes are consistent and controlled by the weaving process. The openings are oblique to the plane of the fabric. The cloth is slightly thicker than monofilaments.

4 Slit-Film. The term as used herein refers to a fiber which has a width many times its thickness. Such fabrics are also called ribbon, split-film, slit-tape, and split-tape. Because of the poor distribution and uneven sizes of the pores, there is a great variation in their retention and filtration capabilities. The fabrics are thin. Slit-film fabrics are not recommended for use as filters.

(b) Nonwoven Fabrics. Nonwoven fabrics include all materials which are not woven or knitted. They consist of discrete fibers, which may have a preferred orientation or may be placed in a random manner and do not form a regular or simple pattern as do wovens. Nonwoven fabrics are composed of either continuous filament or staple filament fibers. Continuous filaments are extruded, drawn and laid in the fabric as one continuous fiber. Staple filaments are cut to length before being laid in the fabric. The engineering properties of nonwoven fabrics are controlled by the fiber type, the geometric relationships of the fibers, and the methods of bonding. Four methods of bonding are described below.

1 Needle Punched. Barbed needles are punched through the fabric web, perpendicular to the plane of the fabric and withdrawn, drawing filaments with them. This causes the fabric to become mechanically entangled. These fabrics have a very complex pore structure and the fabrics are compressible, so the nature of the pore structure changes. This results in a different in-situ filtration performance than might be indicated by isolated permeability and particle retention tests. The fabric is relatively thick and has the appearance of felt.

2 Heat Bonded. The fabric is subjected to a high temperature, which results in the filaments welding themselves together at the contact points. These fabrics have a relatively discrete and simple, though irregular, pore structure and are thin.

3 Resin Bonded. The fabric web is impregnated with a resin which coats and cements the fibers together. Pore structure and

fabric thickness are intermediate between the two fabrics described above. Normally, they have less permeability and fewer voids.

4 Combination Bonded. A number of nonwoven fabrics are a combination of two or more of the above methods to construct a finished product. Due to the variety and numerous combinations available, it is impossible to make an applicable statement regarding pore properties and thickness of this classification of fabrics.

(c) Combination Fabrics. Fabrics have been produced by combining woven and nonwoven fabrics using one or more of the bonding methods described above. Usually, these combination fabrics are produced to enhance a particular property or performance requirement not found sufficient in either of the singular types of fabric construction. Hundreds of such combinations are possible with an equal, or greater, number of finished fabric forms and properties. Each must be evaluated in view of the application being considered.

The 1977 CE Guide Specification CW 02215 (U.S. Army, Corps of Engineers, 1977) states that "The fabric should be fixed so that yarns will retain their relative position with respect to each other. The edges of the fabric should be finished to prevent the outer yarn from pulling away from the fabric." Regardless of the fabric construction, this requirement is necessary to ensure continuous acceptable performance.

(3) Physical Property Requirements. In few other applications is a filter exposed to so many damaging forces as in most types of coastal structures. Consequently, physical property requirements for geotextile filters are more stringent for these applications. Suitable physical (mechanical) properties are not only necessary during the construction process, but in the permanent structure as well. Due to such structure's constant exposure to dynamic loading, from waves and currents, armor and underlayer movement, earth and hydrostatic pressure, and rapid fluctuations, any geotextile used must have sufficient tensile and abrasive strength to retain its integrity throughout the life of the project.

The test methods used to determine geotextile's physical property requirements are primarily textile tests. However, the test methods and requirements referred to herein can be related to the field performance of woven geotextile filters. Evaluation has confirmed successful performance of fabrics having a particular character. Many of the required test results have been verified by more than 20 years of field performance.

If test methods or results and specifications other than those required in this section are employed, they should be thoroughly evaluated to determine if the method and results are applicable to the intended function or performance in the application of interest. Test methods for required physical property determination are described in Appendix C.

(a) Properties Required for All Applications.

1 Tensile Strength. Adequate fabric strength is necessary to withstand dynamic forces, prevent the movement of the geotextile filter through voids in the stone layer above the fabric, as often occurs with

aggregate filters (Dunham and Barrett, 1976), and permit the use of larger stones adjacent to the filter, thereby possibly reducing the overall thickness of the structure (Barrett, 1966; Dunham and Barrett 1976). When armor is removed or rearranged, the fabric's independent strength should also retain the soil (Barrett, 1966; Fairley, et al., 1970) and prevent cavity formation.

2 Elongation at Failure. This is part of the tensile test described in Appendix C. Percent of elongation must be known because excessive elongation will distort and enlarge the pores and change the soil retention capabilities (piping resistance) (Steward, Williamson, and Mahoney, 1977). If excessive elongation is necessary to develop the fabric's ultimate strength, the fabric will probably never develop its required strength in-situ.

3 Seam Strength. It is advantageous to use geotextile filter sheets or panels in large lengths and widths in most applications. The larger panels reduce the number of overlaps required which is the most probable cause for error during construction. Fabrics are manufactured in various widths 1.8 to 5.2 meters (6 to 17 feet), and then sewn together or bonded by cementing or by heat to form large panels as much as 25.6 meters (84 feet) wide. When sections are sewn together the yarn used must conform to the chemical requirements in subparagraphs 2b and 4b. If the seam strengths are too low the sheets may separate and permit piping to develop.

4 Puncture Resistance. Puncture resistance is required to enable the geotextile filter to survive placement of other materials on it during the construction process and to prevent rupture or penetration by the overlying material when the structure is exposed to wave action.

5 Burst Strength. Burst strength must be considered to assure the engineer that the fabric will retain its integrity when subjected to earth forces especially when the material above it contains relatively large voids.

6 Abrasion Resistance. In all types of use, abrasion resistance is important during construction. In one case, fabric was damaged during construction of a French drain merely by placing small filter aggregate into the trench it lined. In coastal structures such as revetments, abrasion resistance is required not only during construction but also throughout the life of the structure, for these structures are subjected to continuous or intermittent wave attacks which result in movement of the overlying material adjacent to the fabric.

(b) Optional Requirements for Special Site Conditions. In certain climatic conditions and geographic locations, it may be desirable to test the geotextile for freeze-thaw resistance, high temperature survivability, and low temperature survivability. When soils in the project site are contaminated, or are subject to infiltration, by high quantities of acids, alkalies, or JP-4 fuel, it may be advisable to test the geotextile's resistance to the specific contaminant. Test methods are described in Appendix C.

(c) Properties Required for Construction Conditions. The physical properties of geotextiles required for specific sites and structures

vary with loadings as well as with function. Loadings may be classified in three service categories:

(1) Severe dynamic loadings,

(2) dynamic and static loadings, and

(3) most stringent placement and drainage.

Severe dynamic loading is characterized by continued abrasive movement of materials adjacent to the fabric due to wave action. Dynamic and static loadings are characterized by more restrictive placement procedures to limit abrasive movement and include gabion applications. The most stringent placement controls and drainage applications nearly eliminate abrasive movement of materials adjacent to the fabric. This category includes weepholes, linings of vertical walls, relief wells, linings for French and trench drains, and wrap collector pipe.

For each loading category certain construction parameters and limitations must be met. In Tables 37 and 38 construction limitations for each category are listed with reference to three specific applications: quarrystone revetment, block revetment, and subaqueous applications. Block revetment includes precast cellular block (a cast or machine-produced concrete precast block having continuous voids through the vertical plane normally with smooth or near vertical sides) and interlocking concrete block (a cast or machine produced concrete block having interengaging or overlapping edges). The subaqueous applications include groins, jetties, and breakwaters; scour protection for piers, piles, and caissons; and toe aprons for bulkheads.

Minimum geotextile filter physical property requirements are shown in Table 39 based on the construction limitations in Tables 37 and 38. Test methods are described in Appendix C. The physical property requirements in Table 39 are not the same as stated in the current Civil Works Construction, Guide Specification, Plastic Filter Fabric, No. CW-02215 (U.S. Army, Corps of Engineers, 1977). Because this report is concerned only with coastal structures, the test methods and requirements set forth herein are based on field performance and verification in these types of structures and relevant laboratory research.

c. Filtering Integrity.

(1) Piping Resistance Criteria. To prevent piping, it is necessary to know the soil retention capability of the geotextile filter or granular filter when considering a filter system. In his extensive and thorough research and development project with geotextiles for filters, Calhoun (1972) developed a special procedure for determining the piping resistance (soil retention capacity) of fabrics. The result of this procedure, described in Appendix C, was to determine the equivalent opening size (EOS) of the fabric.

Knowing that the soil retention ability of a fabric is directly related to the hydraulic pressures, flows and forces it encounters, Calhoun (1972) conducted hydraulic filtration and clogging studies to develop a formula that related the EOS to required performance criteria. For geotextile

Table 37. Construction limitations: quarrystone revetment.[1]

Parameter	CATEGORY A Severe Dynamic Loading	CATEGORY B Dynamic and Static Loading	CATEGORY C Stringent Placement and Drainage
Steepest Slope	1V on 2H	1V on 2.5H	1V on 3H
Min. Gravel thickness above filter	None	None	20 cm
Stone adjacent to geotextile:			
Max. stone weight[3]	1.1 kN	0.78 kN	Gravel
Max. drop height	1 m	1 m	1.5 m
Max. stone weight	1.8 kN	1.3 kN	
Riprap weight range[4]	0.89 - 3.3 kN	0.22 - 2.2 kN	NA[2]
Max. drop height	0.61 m	0.61 m	
Max. stone weight	1.8 - 8.9 kN	1.3 - 8.9 kN	
Max. drop height	placed	placed	NA
Subsequent Stone Layer:			
Max. stone weight	NA	NA	0.67 kN
Max. drop height			1.2 m
Max. stone weight	NA	NA	1.3 kN
Max. drop height	NA	NA	1 m
Max. stone weight	44 kN	44 kN	4.4 kN
Max. drop height	3 m	2.5	placed
Max. stone weight	> 44 kN	> 44 kN	> 4.4 kn
Max. drop height	placed	placed	placed

NOTE: a. Stronger principal direction (SPD) and seams of the geotextile should be perpendicular to the shoreline.
b. There is no limit to the number of underlayers between the armor and the geotextile.

[1]This table may also be used for sand core breakwaters (a jetty, groin or breakwater in which the core material consists of sand rather than stone).
[2]Not applicable
[3]Weight of quarrystone armor units of nearly uniform size.
[4]Weight limits of riprap, quarrystone well graded within wide size limits.

Table 38. Construction limitations: block revetments and subaqueous applications.

Block Revetment[1]	CATEGORY A	CATEGORY B	CATEGORY C
Precast Cellular Block[2]			
Steepest Slope:			
Individual Blocks	1V on 2H	1V on 3H	NA[3]
Cabled Blocks[4]	1V on 1.5H	1V on 2H	NA
Max. block weight	>3.1 kPa	3.1 kPa	NA
Interlocking Concrete Block[2]			
Steepest slope	NA	1V on 2H	1V on 2.5H
Min. gravel thickness Above filter	NA	15.2 cm	15.2 cm
Max. block weight	NA	>3.1 kPa	3.1 kPa
Subaqueous Applications[5]			
Steepest Slope	1V on 15H	1V on 15H	1V on 15H
Stone Adjacent to Geotextile:			
Max. stone weight	8.9 kN	8.9 kN	3.3 kN
Min. drop through water	1.5 m	1.5 m	1.5 m
Max. stone weight	>13.3 kN	>13.3 kN	>3.3 kN
Max. drop height	placed	placed	placed
Subsequent Stone Layer(s)			
Max. stone weight	no limit	no limit	no limit
Max. drop height	NCP[6]	NCP	NCP

[1]Stronger principal direction (SPD) and seams of the geotextile should be perpendicular to the shoreline.
[2]With flat base.
[3]Not applicable.
[4]Precast cellular blocks cabled together in a horizontal plane.
[5]No limit to the number of underlayers between the armor and the geotextile.
[6]As in normal construction practice: the geotextile does not require special limitations in these layers.

Table 39. Minimum geotextile filter physical property requirements.

Property	CATEGORY			
	Test method	A Severe Dynamic Loading	B Dynamic & Static Loadings	C Stringent Placement & Drainage
Tensile Strength[4]-SPD[1]	App. C-1	1.56 kN		0.89 kN
BPD[2]			0.89 kN	
WPD[3]		0.98 kN		0.44 kN
Elongation at Failure	App. C-1	<36%	36%	36%
Seam Strength[4]	App. C-2	0.87 kN	0.80 kN	0.36 kN
Puncture Resistance	App. C-3	0.53 kN	0.53 kN	0.29 kN
Burst Strength	App. C-4	3450 kPa	3790 kPa	1650 kPa
Abrasion Resistance[4]- SPD	App. C-5	0.44 kN		0.27 kN
BPD			0.29 kN	
WPD		0.29 kN		0.15 kN
OPTIONAL REQUIREMENTS				
Freeze-Thaw Resistance	App. C-6	90% of required strength		
High Temperature Survivability	App. C-7	80% of required strength		
Low Temperature Survivability	App. C-8	85% of required strength		
Effects of Acids	App. C-9	90% of required strength		
Effects of Alkalies	App. C-10	90% of required strength		
Effects of JP-4 Fuel	App. C-11	85% of required strength		

[1]SPD = Stronger Principal Direction
[2]BPD = Both Principal Directions
[3]WPD = Weaker Principal Direction
[4]In accordance with the specifications for the tests for these properties, these forces are applied over a width of 25.4 millimeters (1 inch).

filters adjacent to coarse-grained soils containing 50 percent or less particles by weight passing U.S. No. 200 sieve, the piping resistance is calculated using:

$$\frac{D_{85} \text{ of protected soil}}{\text{EOS}} \geq 1$$

where D_{85} is the effective grain size in millimeters for which 85 percent of the sample by weight has smaller grains. For geotextile filters adjacent to fine-grained soils containing more than 50 percent particles by weight passing U.S. No. 200 sieve, the EOS should be no larger than a U.S. No. 70 sieve. Fabric with the largest possible EOS should be specified to promote drainage and reduce the likelihood of clogging. Geotextiles with an EOS smaller than the U.S. No. 100 sieve should not be used as filters.

When the protected soil contains particles ranging from a 2.54-centimeter (1 inch) size to those passing the U.S. No. 200 sieve, only the gradation of soil passing a U.S. No. 4 sieve should be used in selecting the fabric. Whenever the protected soil is so sized or graded that a fabric cannot satisfy the above requirements and the soil is to be protected with a multi-layered granular filter, a geotextile filter will often satisfy the requirements of all but the filter layer immediately adjacent to the protected soil (primary filter layer).

There are additional restrictions regarding the percent of open area (POA) of the geotextile which must be considered in applying the piping resistance formula. The POA determination method is described in Appendix C. These criteria for determining piping resistance have been widely and successfully used by the engineering profession.

The original EOS determination method developed by Calhoun (1972) was based on the sieving of rounded to subrounded sands. Geotextiles rated by this method were used in the filtration and clogging tests which resulted in the piping criteria formula stated above. The 1977 CE Civil Works Construction Guide Specification CW-02215 (U.S. Army, Corps of Engineers, 1977) modified the original EOS determination method by substituting glass beads for sand. The 1977 Guide Specification EOS determination method is described in Appendix C. Many geotechnical engineers and soil testing laboratories who had experience with the sand determination method prior to 1977 indicate the sand behavior is more typical of the material to be protected. Most often stated objections to beads are:

(a) they develop static electricity;

(b) there is a size problem: many are not "true" when received from the manufacturer;

(c) a continuous breakdown of the beads occurs during sieving;

(d) different results are obtained for the same geotextile when beads are used compared to the results when sand is employed: generally beads yield a larger apparent opening value (smaller sieve number) than sand (i.e., beads - EOS equals No. 50 sieve vs.

sand - EOS equals No. 70 sieve), on some occasions the discrepancy is reversed. (B.R. Christopher, P.E., Corporate Laboratory Director, STS Consultants Ltd. (formerly Soil Testing Services, Inc.), Northbrook, Illinois, personal communication, 1979-82).

Other sources have stated similar experiences and indicate inconsistent results are obtained when sand is replaced by beads.

Geotextile filter selection criteria for piping resistance are the same for all applications in coastal structures. The criteria are based on the work of Calhoun (1972); the U.S. Forest Service criteria; experience with laboratory testing, field experiments, installations and monitoring as presented by Steward, Williamson and Mahoney (1977); and the authors' (of this section) personal experience, performance records, and communication with users and researchers. Geotextile filters meeting the Calhoun EOS determination criteria have had field verification (service records) for more than 20 years.

(2) Clogging Criteria. In shore protection structures (such as revetments), geotextile filters may be exposed to severe static and dynamic loading, turbulent flows, rapid fluctuations, high-pressure differentials, and sudden or regular drawdowns. Designers primarily concerned with subsurface drainage must recognize the necessity for more stringent property and performance criteria for fabrics being considered for this environment. It is especially true with respect to the filtration and clogging performance, because, if the filter clogs, it could cause a more severe problem than if it had been omitted. Usually underdrains have low rates of flow and relatively low hydraulic gradients. Due to the large-grained sand present in many coastal areas, filters adjacent to French and trench drains and surrounding collector pipes are often exposed to higher flow rates than would normally be expected in these applications. It is the responsibility of the designer to specify a geotextile filter that retains the soil being protected, yet will have openings large enough to permit drainage and prevent clogging.

Many fabric suppliers provide fabric permeability and waterflow rate at a specified head as fabric performance criteria; however, these data are of little use in establishing filter-clogging criteria.

(a) Corps of Engineers Criteria. Calhoun (1972) developed the most widely used filtration-clogging geotextile filter criteria in 1972 after an extensive 3-year research effort. While the criteria were rather simple, they were based on numerous hydraulic-soil-fabric filtration and clogging tests. Using his method described in Appendix C, Calhoun determined the EOS of the fabric and in addition determined the POA.

As mentioned in the discussion of piping resistance, with certain restrictions for fine-grained soils, Calhoun's criteria allowed the ratio of the soil's D_{85} to the fabric's EOS to be equal to or greater than 1. The criteria also had an added limitation that no woven fabric should have a POA less than 4 percent nor EOS with openings smaller than U.S. No. 100 Standard Sieve. Calhoun established that the larger the POA, the less the fabric was susceptible to clogging.

The current 1977 CE Guide Specification (U.S. Army, Corps of Engineers, 1977) introduced the gradient ratio (GR) based on Calhoun's original work. Determination of gradient ratio is set forth in Appendix C.

(b) Forest Service Criteria. The U.S. Department of Agriculture Forest Service (USDAFS) has conducted numerous laboratory and field tests, including an evaluation of geotextile filter performance in various types of structures. Their criteria for piping resistance (soil retention) and clogging are similar to Calhoun's, as discussed above and stated in Appendix C, the EOS-POA combined criteria. The service does have some disagreement with the current 1977 CE Guide Specification (U.S. Army, Corps of Engineers, 1977) as discussed by Steward, Williamson, and Mohney (1977). They feel that the currently recommended GR test should be modified to represent the range of varying seepage rates and fabric strains accompanying the enlargement of openings in nonwoven fabrics due to stretching anticipated in the field, and that intermittent flow should be added. They suggest that the GR test has not been confirmed by monitoring field performance. Concern [illegible] also expressed that due to higher elongation, EOS of nonwoven fabrics will be more variable and more subject to change under load than that of woven fabrics.

For all critical and severe filter applications the U.S. Forest Service indicates that *only woven geotextiles should be used* (Steward, Williamson, and Mohney, 1977). The USDAFS definitions of these terms are quoted below:

"Critical: Projects where failure of the filter could result in failure of an expensive or environmentally sensitive part of a project, such as:

(1) rock blankets greater than or equal to a 3-foot-horizontal thickness,

(2) retaining structures,

(3) road fills greater than 10 feet in height,

(4) underdrain trenches greater than 5 feet in depth, and

(5) bridge repair.

Severe: Conditions of moderate to high seepage out of erodible soils with a hydraulic gradient evident moving from soil toward the filter, such as:

(1) spring areas,

(2) soils with flowing ground water, and

(3) soils with high internal hydrostatic pressure."

Both the above definitions seem applicable to most coastal applications. Calhoun (1972) also concluded that only woven fabrics be used in coastal projects. The Forest Service indicates a preference for the woven filters and that the sometimes "lower material cost of the lightweight non-woven fabrics for critical or severe seepage conditions appear to be outweighed by

the risk and consequence of possible failure at this time". They also state that in similar installations, graded aggregate filters have a 50 percent chance of functioning properly, while woven geotextile filters have a rate near 100 percent.

(c) Combined Criteria. In order to develop a laboratory and field performance verified geotextile selection criteria for filtration-clogging properties, the authors of this section relied on the experience of knowledgeable users, their own personal experience, and a combination of parts of reports citing criteria relevant to coastal applications by Calhoun (1972), Steward, Williamson, and Mohney (1977), and CE 1977 Guide Specification (U.S. Army, Corps of Engineers, 1977).

To achieve desired clogging resistance, woven geotextile filters adjacent to soils containing 50 percent or less particles by weight passing through a U.S. No. 200 sieve, should have an effective POA equal to or greater than 4.0 percent. (When overlayed with stone, the POA of the geotextile is the effective percent open area. If half of the geotextile is covered by flat based concrete blocks without a gravel layer between the fabric and the blocks, a POA equal to or greater than 8.0 percent is required to yield an effective POA equal to or greater than 4.0 percent.)

Nonwoven geotextiles in the same application should have a gradient ratio equal to or less than 3.0. This same gradient ratio is used as the criteria for selection of all geotextiles adjacent to soils with more than 50 percent particles by weight passing the U.S. No. 200 sieve, or soils with a very slight gradation curve or those that are skip-graded (gap-graded). Geotextiles with the largest possible POA available in the required EOS sieve number should be specified.

As stated previously, ASTM Subcommittee D-18.19/D-13.61 is developing test methods for geotextiles. When these, or other, test determination methods and formulas are submitted to the specifier, they should be evaluated to determine if their results meet the requirements discussed above. It is recommended that both sets of tests be conducted and the results correlated to the requirements stated in this report.

d. Placement. The geotextile filter must be laid loosely, not in a stretched condition but free of wrinkles, creases, and folds for all applications on slopes and beneath jetties. When the slope continues above and beyond the structure, the filter should be keyed-in by being placed in a trench at the upper terminus of the structure. When a gravel layer is placed on the geotextile, it must have sufficient permeability so that it does not reduce the flow from the filter. The largest size sheets available should be used to reduce the number of overlaps required. Overlaps of adjoining sheets should be a minimum of 46 centimeters (18 inches) and staggered for installations in the dry. For underwater applications, the overlaps should be 1 meter (3 feet). Strict inspection and enforcement is required with respect to drop height limitations and overlaps.

On slopes, construction begins at the toe and then proceeds up the slope. Horizontal underwater placement (such as groins, jetties, and scour

protection for vertical walls and piers) starts at the shoreward end and proceeds away from the shore, or starts adjacent to the protected structure and proceeds to the outer limits of the scour protection.

When securing pins are required to prevent the geotextile from slipping during construction, they shall be 3/16-inch in diameter, of steel, pointed at one end and fabricated with a head to retain a steel washer having an outside diameter of no less than 3.8 centimeters (1.5 inches). The pins should have a minimum length of 46 centimeters when used in soils having a medium to high density. For loose soils, longer pins should be used. They should be inserted through both strips of overlapped fabric at the midpoint of the overlap. The maximum pin spacing along overlaps should be 0.6 meter (2 feet) for slopes steeper than 1V on 3H, 1 meter (3 feet) for slopes of 1V on 3H to 1V on 4H, and 1.5 meters (5 feet) for slopes flatter than 1V on 4H. Additional pins shall be installed as necessary to prevent any slippage of the geotextile, regardless of location.

e. Repair Method. If the geotextile filter is damaged during the placement of the fabric or of the stone (or blocks) on the fabric, it should be repaired as follows: Cut the damaged part of the fabric out of the sheet and position an undamaged piece of geotextile filter, 1.2 meter (4 foot) longer in each direction, where the fabric has been removed. Extend the edges of the new fabric 0.6 meter (2 feet) beyond and under the edges of the undamaged original filter.

f. History of Uses in Coastal Construction. The first use of geotextiles was as a filter beneath an interlocking concrete block revetment on the Atlantic coast in South Palm Beach, Florida, in 1958 (Dallaire, 1977). The fabric used was woven of monofilament yarns of polyvinylidene chloride (saran), containing stabilizers to make the filaments resistant to ultraviolet and heat deterioration. The equivalent opening size (EOS) was equal to a U.S. Standard Sieve No. 100 and the percent of open area (POA) was 4.6 percent. Physical properties were as follows: tensile strength approximately 890 newtons (200 pounds) (warp), 445 newtons (100 pounds) (fill); elongation at failure less than 33 percent; burst, 1 790 kilopascals (260 pounds per square inch); puncture, 310 newtons (70 pounds); abraded strength, 250 newtons (57 pounds) (warp), 85 newtons (19 pounds) (fill).

In the following 4 years, geotextile filters were used in a number of coastal structures on the east coast of the United States. In every instance, the fabric was the same as in the first use at South Palm Beach. While the fabric performed satisfactorily in these installation, field observations during construction led to the conclusion that construction would be simplified, and a superior structure would result, if a filter could be developed with higher tensile strength, burst, puncture and abrasion resistance for use in conjunction with quarry stone construction materials. Development of a geotextile woven of polypropylene monofilament yarns consisting of at least 85 percent propylene and containing stabilizers and inhibitors to make the filament resistant to ultraviolet and heat deterioration was completed in 1963. The new fabric had an EOS equal to a No. 70 U.S. Standard Sieve and a POA of 5.2 percent. Physical properties were as follows: tensile strength approximately 1 690 newtons (380 pounds) (warp), 979 newtons (220 pounds) (fill); elongation at failure less than 30

percent; burst, 3 720 kilopascals (540 pounds per square inch); puncture, 620 newtons (140 pounds); abraded strength, 440 newtons (100 pounds) (warp), 310 newtons (70 pounds) (fill).

In 1969 the U.S. Army Engineer District, Memphis inspected three bridge abutments protected by geotextile filters overlayed with 560-newton (125 pound) stone. In one abutment built in 1962, the fabric, similar to the 890-newton tensile strength fabric referred to above, had numerous holes attributed to abrasion and could be easily torn by hand. The other two abutments, built in 1964 using the stronger, 1 690-newton tensile strength fabric, were in excellent condition and no evidence of loss of strength was apparent (Fairley, et al., 1970).

The following list identifies the first uses of geotextile filters in coastal structures by U.S. government departments and agencies:

1961 - U.S. Navy, U.S. Naval Station, Mayport, Florida. Beneath stone revetment.

1962 - U.S. Army Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Virginia. Beneath interlocking concrete block revetment (Hall and Jachowski, 1964).

1962 - U.S. Department of the Interior, National Park Service, Colonial National Historical Park, Yorktown, Virginia. Beneath stone revetment and repair of damaged shoreline riprap.

1963 - U.S. Department of Agriculture, Forest Service, Lake Winnibigoshish, Chippewa National Forest, Minnesota, Erosion Control beneath gabions (first filter application with gabions).

1964 - U.S. Air Force, Capehard Marina, Tyndall Air Force Base, Florida. Beneath stone breakwaters.

By 1966 woven geotextile filters had been included in the following types of coastal structures in North America: filters beneath stone and interlocking concrete block revetments, linings for the interior of vertical seawalls (bulkheads) to permit the relief of water through weepholes and the joints (tongue and groove, king pile and panel, T-pile and panel), wrapping for collector pipes and "french drains," beneath stone jetties, groins and breakwaters, security for the slopes of "sand core" jetties, linings for the interior of steel cells, and scour protection around steel cells and piers of drilling platforms down to a 46-meter (150 foot) depth as in the North Sea (Barrett, 1966).

Lake Texarkana, Texas, was the location of the first installation of a nonwoven textile in a coastal structure in the United States. Construction in 1976 consisted of a precast cellular block revetment lying directly on the fabric. The geotextile filter was composed of 100 percent polyester continuous fiber, the filaments mechanically interlocked by needle punching. The EOS equaled a No. 100 U.S. Standard Sieve, other properties were: tensile strength, 1 330 newtons (300 pounds); elongation, 65 percent; burst, 3 450 kilopascals (500 pounds per square inch); abraded strength, 730 newtons (165 pounds).

3. Other Forms of Plastics Used in Coastal Structures.

a. Flexible Forms for Concrete. High strength fabric such as nylon may be used in conjunction with concrete to control erosion. To form slabs, the fabric is put down as a double layer along a bank or shoreline and acts as a mold form for concrete that is injected into it. Figure 83 shows two types of double layer fabric forms. Figure 84 shows installation of a concrete filled form.

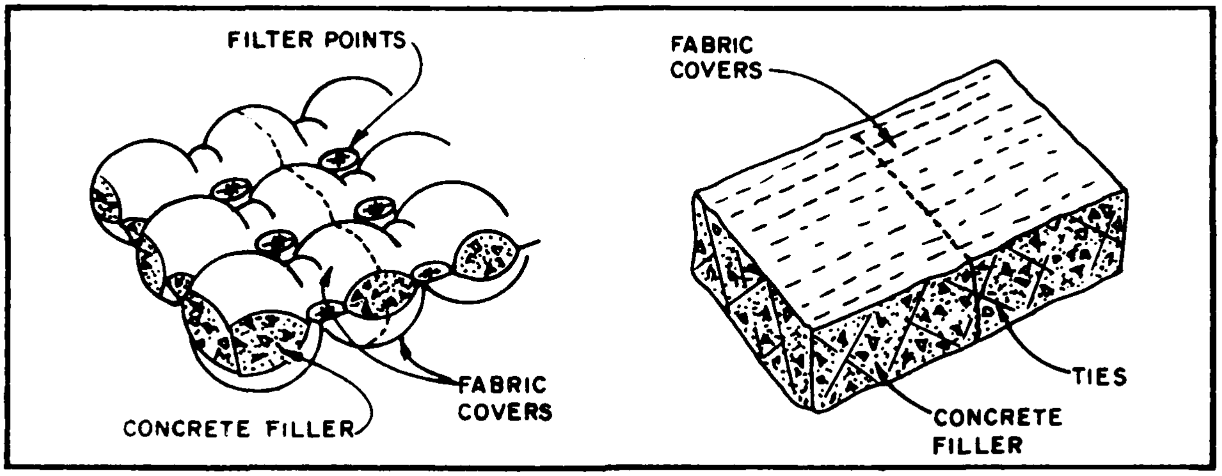


Figure 83. Two types of double layer fabric forms (courtesy of Fabriform).

Grout-filled fabric tubes may be arranged in various configurations along the shoreline. They are useful as groins, dikes, breakwaters or weirs. Figure 85 shows an arrangement of tubes and a filling point. Figure 86 shows the use of fabric pillows as concrete forms for erosion control. Koerner and Welsh (1980) give examples of slab and tube forms.

b. Sheet Forms. Synthetic sheet materials made of polyethylene, vinyl or rubber are used as linings and as covers for controlling water seepage and preventing pollution. These liner-type materials may be bonded together to form a large continuous sheet. As such it is useful in lining storage ponds or pits where coastal pollution is a problem. Synthetic sheet materials are also utilized in harbors to control and to clean up oil spills. Flexible plastic sheeting is held between floats so that it passes through the surface layer as a pollution dike (Fig. 87). The polluting material is retained within the flexible floating dike. Such diked areas can be set up in advance of operations that might result in a spill. For example, the regular off-loading of oil at a cargo terminal would require that a containment boom be on standby or deployed in a particularly environmentally sensitive location. The confined retained pollutant can then be cleaned up by a simple surface skimming operation.

c. Molded Forms.

(1) Guards and Rubbing Strips. Fenders or guards are frequently fabricated from rubber and high strength synthetic plastics or plastic-fabric combinations. Examples of these structures are illustrated in Figure 88.

Figure 84. Double layer fabric forms being installed (photo courtesy of Fabriform).

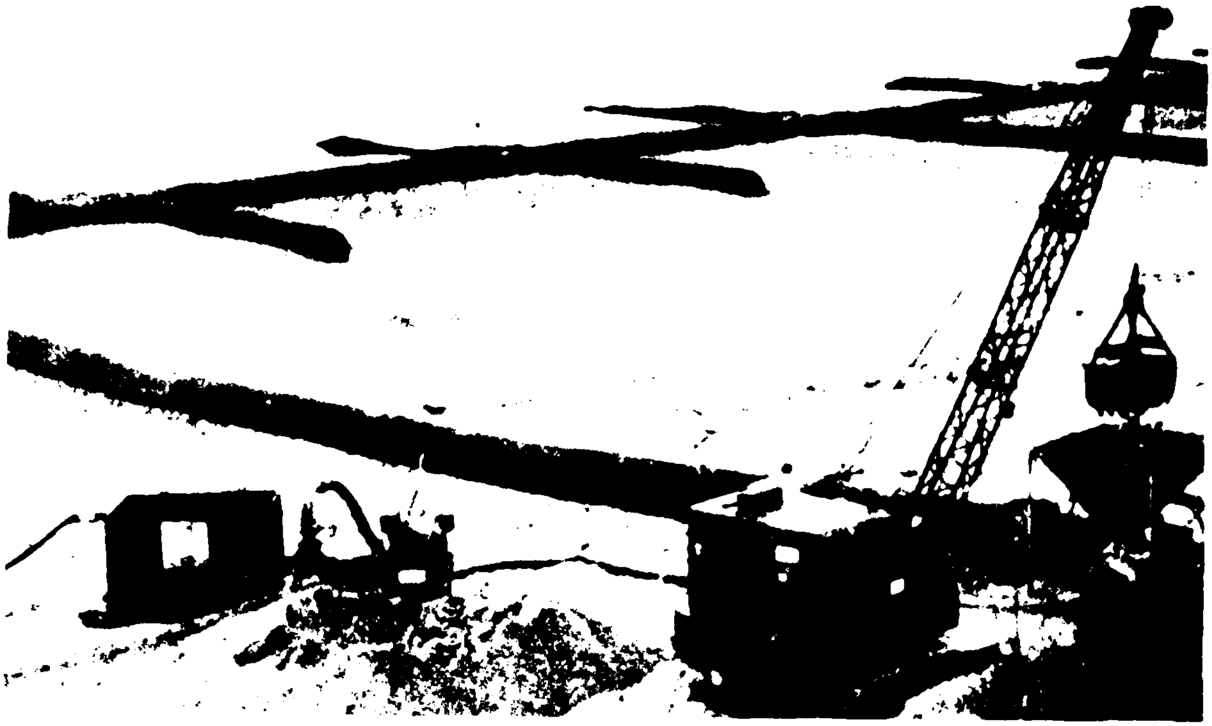


Figure 85. Longard tubes being filled with sand for beach nourishment project, North Sea Coast Germany (photo courtesy of Langeoog).

Figure 86. Concrete-filled bags of synthetic fiber used for shore protection (photo courtesy of Fabricast).

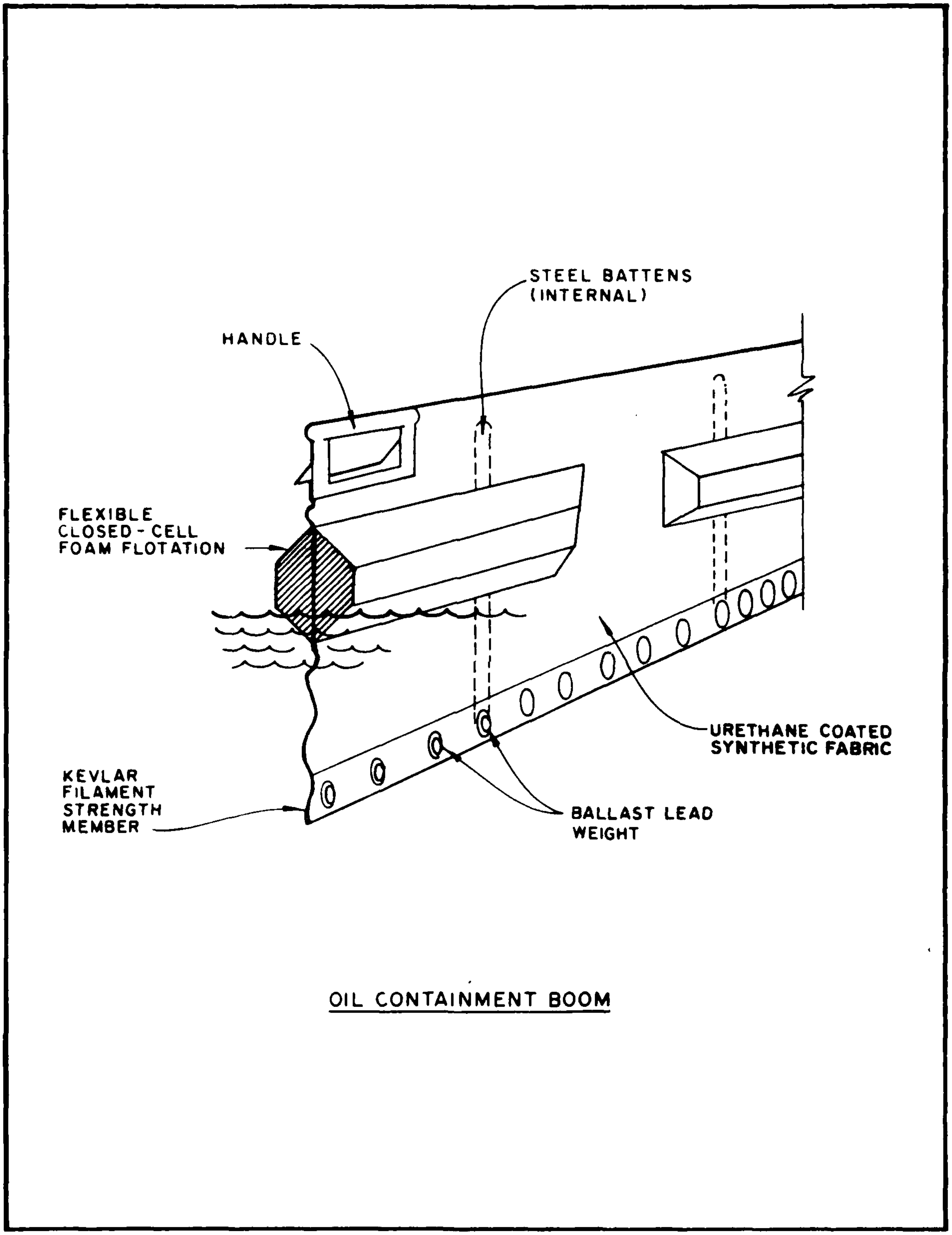


Figure 87. Oil containment boom made of synthetics.

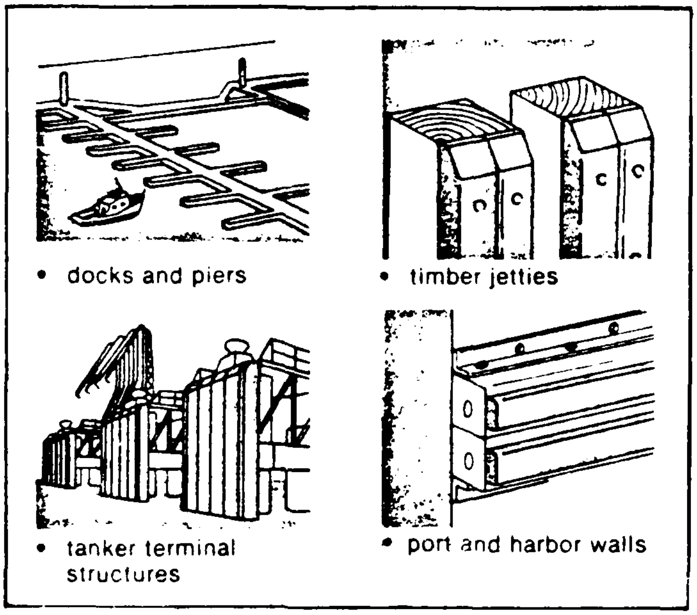


Figure 88. Typical uses of molded high density polyethylene (courtesy of Schlegel Corporation).

(2) Fenders and Bumpers. Rubber and high density polyethylene (HDPE) are excellent and widely used materials for fenders and bumpers. High density polyethylene has excellent properties for marine application such as sliding fenders. It has excellent low friction properties, good toughness, and resistance to abrasion and impact damage. High density polyethylene may be cross linked to form a three-dimensional structure to make it even higher in strength. However, its elongation and flexibility properties are reduced as its strength is increased.

Polyethylene outlasts wood rubbing strips on fenders four to five times, is easily machinable or extrudable, and requires little maintenance. It also has greater fire resistance than wood. This fire resistance can also be enhanced by certain formulation modifications of the polyethylene.

Rubber, in the form of tires and molded shapes, is utilized with excellent success as rubbing bumpers. Old tires are frequently found in harbors as bumpers for small craft. The energy absorption capacity of old tires is unpredictable and not relied upon for larger vessels. For larger vessels, a chain net of tires over a rubber or HDPE cushion block to provide energy absorption may be used. Figure 89 shows such an application.

d. Pipe Forms

(1) Fiber Reinforced Plastic (FRP). This special pipe is coming into wide usage today. It is often referred to as RTRP (reinforced thermosetting resin pipe). As mentioned above, thermosetting resins such as

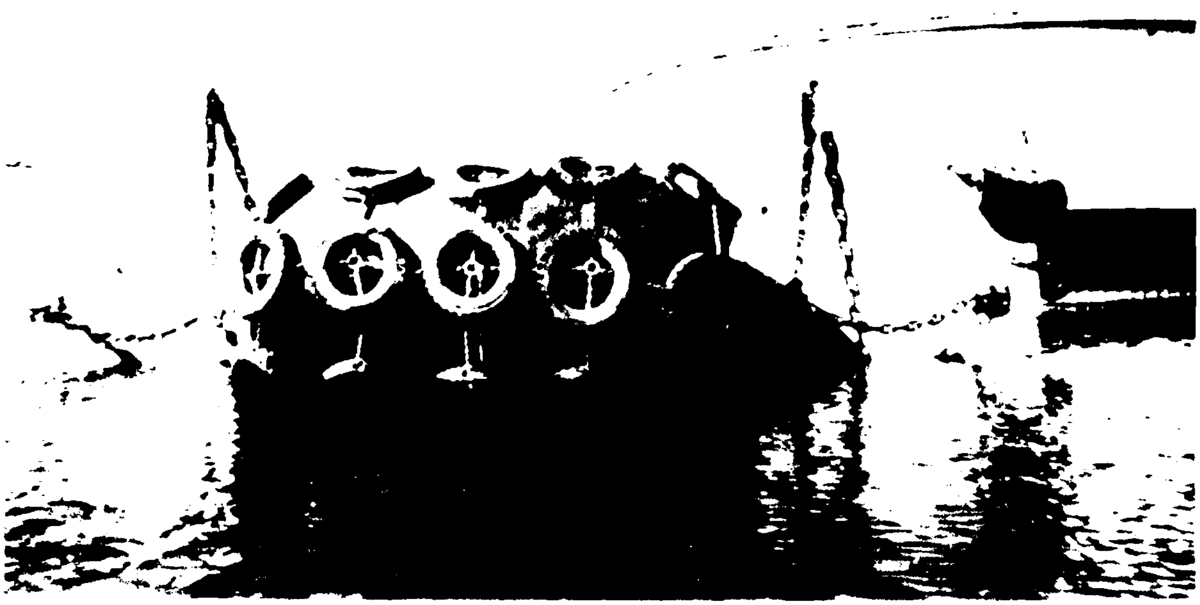


Figure 89. Sea cushion with tire chain net (photo courtesy of Seaward International).

epoxy or polyester may be used in combination with fiberglass to manufacture a tough corrosion-resistant pipe. This pipe is utilized in and around the waterfront to avoid the necessity of corrosion procedures such as coating, coating and wrapping,or cathodic protection.

The material costs of FRP pipe are higher than steel pipe. However, installation costs for FRP pipe can be significantly lower than that of steel pipe due to its lightweight, ease of handling, and capability of making field joints. In fact, the total installed cost of FRP piping is usually lower than that for steel pipe in the same size range.

(2) Nonreinforced Pipe. Nonreinforced plastic pipe in the smaller size range, to about 25-centimeter (10 inch) diameter, is used in many construction projects. It does not have the structural strength of FRP in large diameters but is sufficiently strong in most small diameter applications. Nonreinforced plastic pipe is produced by the extrusion process. The present technology for pipe extrusion uses PVC powder compounds produced by cold blending techniques that do not require high-cost intensive mixing equipment. Nonreinforced plastic pipe has a large use in the electrical industry as electrical conduit and, because of its lower cost and excellent corrosion resistance, is finding expanded use as a water and drainage pipe.

e. Epoxy Grouts. Epoxy resins, when mixed with sand, form a chemical grout which has excellent chemical and physical properties. These grouts may be used to patch cement construction such as roadways, or to patch certain worn or corroded metal parts. These epoxy grouts have superior adhesion properties with high strength and corrosion resistance. Many other grout types are available, e.g., silicates, acrylics, and lignin.

4. Environmental Considerations.

a. General. The environment interacts and combines with the magnitude and duration of stress, strain, and temperature to further alter material response and strength of plastics. Chemical environments, (for example, ultraviolet (UV) exposure, contact with petroleum products and sustained elevated temperature), can have profound influence on performance and hence must be a consideration in the design and use of plastics. However, many synthetics have a high chemical stability and resistance to chemical attack by acids and alkalies. The failure to design for environmental effects as they interact with sustained stress or strain has been the chief cause of failure of plastic products.

Fillers and plasticizers alter the basic response and strength of plastic materials. Fillers (e.g., clay, limestone, carbon black, and other inert materials), introduced to increase stiffness, improve processing characteristics, or lower costs, may also be used to improve UV resistance or heat resistance. Plasticizers change the physical properties of plastics such as impact resistance, flexibility and toughness and abrasion resistance. The introduction of strong fibers, such as glass, will improve strength, stiffness, and dimensional stability.

Stabilizers are an important group of additive materials, used to increase the resistance of plastics to the deteriorating influence of weather, UV light, or radiation. Stabilizers are also used to retard degradation by heat. Flame-retardant chemicals, such as phosphorous and halogens, can be incorporated in the molecular structure to improve fire resistance.

Plastics in common use in the coastal environment, such as the epoxies, polyesters, polyethylene, polypropylene and polyvinyl chloride, are generally not considered to be biodegradable. However, these plastics in virtually all structural forms (such as tanks, pipes, bouys or geotextile fabrics) have a high corrosion deterioration in the coastal environment and when exposed to chemicals, except for some of the aliphatic solvents, such as keytones.

b. Geotechnical Fabrics. Atmospheric temperature, chemicals (in concentrations normally found in soils), and wetting and drying are factors having little or no effect on geotextiles conforming to the chemical and physical requirements stated in the text and Table 39. Trees may grow through the fabric. In the few cases where this has been observed, there was no detrimental effect to the function of the filter because the geotextile was sealed tightly against the tree trunk at the point of penetration.

No standard test method has been developed to determine the biological resistance of geotextiles. However, all investigators have concluded that fabrics composed of the synthetic polymers described earlier, are inert to

biological attack, with the possible exception of polyamide (nylon). Research has shown, however, that bacterial activity in the fabric interstices can clog a fabric, reducing its permeability. B.C. Beville, U.S. Department of Agriculture, Soil Conservation Service, Orlando, Florida, in 1968 performed the following test (Calhoun, 1972). Two slotted collector pipes were installed in separate trenches. Each was wrapped with a geotextile filter of different physical type and chemical composition. In a matter of weeks, the nonwoven glass fiber fabric on one pipe became clogged with an iron sludge. The sludge was formed by iron bacteria that oxidized and precipitated iron into the water. There was no sludge buildup on the woven polyvinylidene chloride cloth on the other pipe.

Other factors discussed in detail below can also have an adverse effect on the performance or physical properties of geotextiles.

(1) Ultraviolet (UV) Radiation. All synthetics discussed previously, without UV stabilizers, are subject to degradation when exposed to UV radiation. The fabric will be exposed to UV rays during construction. The length of time of exposure will vary with the size of the project and the construction sequence. In a drainage installation, when completed, there is no concern for the effects of UV radiation. However, for certain types of coastal structures, such as revetments, UV resistance must be considered. Continuous or intermitent UV exposure may result from any one or a combination of the following:

(a) The stone armoring may be relatively thin and rays penetrate to the fabric through voids in the armor;

(b) the armor may be precast cellular block, cast with a hole through the concrete from the top to the bottom of the block, permitting daily exposure to UV rays;

(c) armoring materials may be rearranged or removed by storm or other occurrence exposing the previously shielded fabric; and

(d) a construction oversight may have permitted the geotextile filter to be exposed after the structure's completion.

The 1977 CE Guide Specification (U.S. Army, Corps of Engineers, 1977) requires that the fabric "contain stabilizers and/or inhibitors added to the base plastic if necessary to make the filaments resistant to deterioration due to ultraviolet and/or heat exposure." For most coastal installations the phrase "if necessary" should be eliminated.

Of the synthetics discussed, in an untreated state (no stabilizers or inhibibitors added to the polymer) polyester has the greatest resistance and polypropylene and polyethylene the least resistance to UV degradation. Steward, Williamson, and Mohney (1977) report that untreated nonwoven polypropylene and polyester fabric samples completely disintegrated within 18 months when left exposed in the field. Bell and Hicks (1980) indicate that, when constructed of the same fiber and having an equal amount of UV stabilizers, woven monofilament fabrics would be the most resistant to UV radiation, multifilament woven and the nonwoven fabrics would have intermediate resistance, and slit-film woven would be the least resistant.

One monofilament woven polypropylene fabric in which carbon black was incorporated in the filament during the extrusion process retained satisfactory strength properties after 11 years of exposure (no cover material) in a coastal environment (Soil Testing Services, 1980).

As yet, no standard test has been developed to measure the length of time fabric, either untreated or treated, may be exposed to UV before harmful degradation takes place. ASTM Subcommittee D-18.19/D-13.61 is currently attempting to develop such a test method. As stated above, there are numerous design reasons for UV stabilizers being necessary in geotextiles for coastal structures, especially in the absence of a method for determining fabric life.

(2) Fire. The melting point varies with the polymer used in the fabrics from 135° to 260° Celsius (274° to 500° Fahrenheit). If fire generates heat beyond the fabric melting point, it will alter the geotextile filter's piping and permeability performance. Some polymers will burn (support combustion), while others only melt.

(3) Ice. Ice formation within the structure of thick nonwoven fabrics will enlarge the pore openings. Depending on the polymer and fabric construction, some recovery (of unknown extent) may take place. The soil retention capability will be reduced.

(4) Kinetic Energy, Kinetic energy, in the form of direct wave attack on unarmored geotextiles may cause rupture. Wave energy transmitted by armor stone may damage covered geotextiles, if requirements described in Tables 37 and 38 are not met.

(5) Abrasion. Abrasion can tear fibers, weakening the fabric as mentioned earlier. Fabric can be abraded by overlying material during construction and storms, and by waterborne debris if the cover is removed.

(6) Vandalism. If the fabric is not protected by a cover of earth or armor it can be damaged by vandalism.

X. RECYCLED AND OTHER MATERIALS

1. Introduction.

In emergency situations or when funds are lacking and the need is great, almost any material, with a specific gravity greater than water, has been used either as a temporary or permanent protective device against damaging waves or currents. Even for temporary protection, materials with a specific gravity of less than 1.5 are of little value. Other materials that may provide emergency or short-term protection may be so difficult to recover, or remove, as to be undesirable. Others may be environmentally undesirable due to hazards to bathers, visual or chemical pollution, or there may be the possibility that waves or currents may transport the material to an undesirable location or cause undue scour.

New materials are continually being offered for coastal installations, but durability and resistance to fatigue and chemical breakdown are vital to the economic life of a coastal structure and, too frequently, only a long period of time will determine how the untested new material will function.

2. Concrete.

a. General. Salvaged concrete may be used as found in its original form so long as lifting and transport equipment can handle it. It may be of reinforced or unreinforced concrete broken into sizes more easily handled, or it may be crushed and reduced to sizes ranging from sand to cobbles.

b. Concrete Rubble. Concrete broken into sizes capable of being transported and handled by conventional rock-placing equipment can be used in the same manner as rock rubble for the armor and underlayers of rubble-mound structures. It is generally of two types--unreinforced or reinforced concrete. Unreinforced is preferred. If reinforcing steel is protruding, it is unsightly and dangerous to bathers or recreationalists climbing on it. If possible, protruding sections of steel should be cut off. In saltwater the exposed steel will corrode rapidly and split the pieces of concrete into smaller units and reduce their effectiveness to resist the force of waves or currents.

(1) Revetment. The most common use of concrete rubble is in revetment. It may be used for armor stone or for the underlayer and design slope and sizing should follow the same design procedure as for rock. It must be kept in mind that concrete only has a specific gravity of about 2.3 to 2.5 and does not have the hardness of most stone so it will have a limited life. In place, it generally presents a somewhat unattractive appearance as compared to rock but, if in the wave wash area, will be abraded into a less angular shape and appear similar to waterworn rocks. It is acceptable as an underlayer beneath armor rock and near urban areas may be less costly.

The primary use of salvaged concrete or concrete rubble in revetments is for emergency, low costs, or temporary revetment of an eroding bank or bluff. It is generally available for the cost of hauling an in many areas

like the coastline of the Gulf of Mexico, the southeastern United States or parts of the shorelines of the Great Lakes may be the only protective material immediately available. Sources of salvaged concrete for use in revetment are broken highway or landing strip paving, foundations for structures, broken piles or light standards, manholes, large sewer or water pipe. Thin slabs, particularly those reinforced with wire mesh, should not be used as they tend to form flat planes upon which other materials slide into deeper water and the exposed mesh is hazardous to recreationalists and the rusting of the mesh causes rapid deterioration.

(2) Groins. The application of salvaged concrete is the same for groins as revetment but as groins are usually located in recreational areas the concrete is much less desirable from an esthetic and safety point of view.

(3) Jetties. Concrete rubble is generally not desirable as armor material for jetties unless the jetties are located in small bays or lakes where waves are of limited height. The several thousand pieces of armor material required are usually not available in design size from broken concrete. Jetties are also usually designed for a long life and the concrete blocks tend to wear rapidly or disintegrate. Concrete rubble may, however, be used as graded core material.

(4) Breakwaters. Concrete rubble is generally undesirable for the armor or underlayers of a breakwater unless it is in a small bay or lake. Wave action may be too severe and it is not feasible to obtain an adequate quantity of design size pieces. Concrete rubble is acceptable as a filler within the core section, as long as it is well mixed with the remaining core material to avoid excessive voids.

c. Crushed Concrete. Equipment is available now to economically crush unreinforced concrete to most any size and gradation desired. Because of the need to completely rebuild miles of old highways, crushed concrete will, in some areas, compete with the cost of crushed stone.

(1) Protective Structures. The principal use for crushed concrete in breakwaters, groins, and jetties would be for the core and bedding layer. Density is not so important here as for the cover layers but the crushed concrete should satisfy the same size, gradation and durability requirements as those established in the SPM (U.S. Army, Corps of Engineers, Coastal Engineering Research Center (CERC), 1977) for stone. The same criteria apply to the use of crushed concrete for use as filter layers in revetments, seawalls and bulkheads, and special measures may be required to control the amount of dirt in a crushed concrete mix.

(2) Roads and Parking Lots and Storage Areas. Crushed concrete is frequently used as a base course for roads, parking, or storage areas, particularly in commercial harbors. Properly graded, it is as effective as crushed stone and in urban areas may be less costly.

d. Unbroken Concrete. Unbroken concrete would normally be so large as to be a supplement to cover stone. It would consist of foundation blocks, light standards, concrete piles, manholes and other reasonably compact concrete structures weighing between 0.44 and 88 kilonewtons (100 and 20 000

pounds). They are generally of an awkward shape to place and, if made of reinforced concrete, can have severe handling and corrosion problems, particularly if used in saltwater. They are generally unsightly and can be difficult to recover when no longer needed.

Concrete barges or concrete hulled ships have, on a few occasions, been used in breakwater, groin or jetty construction. They may be incorporated into the mass of a breakwater or jetty, or may be used singly or in a line to act as a groin. In general they have not served well because their smooth sides and bottoms and large surface area compared to mass permit them to slide or tip out of position. The interior of these barges or ships may be difficult to fill with ballast and they are subject to the same deterioration problems of these slabs of concrete. Such barge or ship hulls can be extremely difficult and costly to remove or salvage.

(1) Temporary or Emergency Protection. This is the most prevalent use of unbroken concrete units and many times does more harm than good. Unbroken concrete units are usually large enough that they should have an underlayer, or bedding layer, of smaller rocks, as in the design of a rubble-mound stone structure. Shapes such as light standards and pilings are usually too long and rigid to act as flexible and effective units, and in general there is little variety in size or shape to provide a well-graded section such as can be done with stone. Without a bedding layer, these units tend to work into the sand bottom and can be very difficult to remove. However, in emergencies they may be the only medium to high density material available and may be used pending later availability of properly graded stones.

(2) Supplement to Armor Stone. Generally, for rubble construction, these unbroken concrete units are not available in a sufficient range of sizes to be used as armor stone. However, if they fit some of the design sizes for armor stone, and esthetics and the safety of recreationalists are not a controlling condition, they may be used in combination with armor stone to reduce costs.

(3) Supplement to Core Stone. Unbroken concrete units are frequently used in conjunction with core stone to simply provide bulk and reduce costs. Care must be taken to fill all voids inside and around these units so that they become an effective part of the core. Problems may be encountered if their dimensions do not allow them to fit within the core boundaries and they should not be placed so that large flat surfaces are near horizontal thus encouraging the sliding of other stones across them.

3. Asphalt.

a. General. The primary types of asphalt mix used as a salvaged material in shoreline structures are the asphalt and concrete mixes and the asphalt and sand mixes. Both are used much in the same manner as salvaged concrete; i.e., as a substitute for stone. Depending on the proportion of asphalt, both the mixes tend to be of a lower specific gravity than stone or concrete and for this reason are less desirable. Both are less durable than stone or concrete. Because of its black to brown coloration it is less desirable from an esthetic point of view than concrete or rock.

It is possible through heat processing to melt asphalt down and reuse it as a mixing agent but the cost is prohibitive and the material is of no value for shoreline structures.

b. Asphalt in Rubble Structures. Broken asphalt concrete can be used in the underlayer if the same design criteria are followed as for stone. As a cover layer it is not desirable as it is of low specific gravity, is not as durable as stone or broken concrete, and due to its color and appearance is not esthetically appealing. Asphalt-sand has little durability, a characteristic that makes it undesirable in the cover layer.

c. Crushed Asphalt Concrete. Crushed asphalt concrete or asphalt-sand is an acceptable substitute for stone as core or bedding material in coastal structures but must be used with care as filter material because of the difficulty of obtaining and maintaining an adequately graded mix to properly act as a filter. The most common use is as a base material for roads, parking lots, and storage areas in the same manner as discussed for broken concrete. Either broken or crushed asphalt concrete or asphalt-sand may be used as fill material so long as the voids can be filled.

4. Concrete Blocks and Bricks.

a. General. Salvage material, consisting generally of hollow concrete blocks, cinder blocks and bricks, may be used in random placement. These materials are seldom used unless for emergency protection or of economic necessity.

b. Concrete Blocks. These are generally hollow blocks salvaged from dismantled buildings or broken in production during the curing period. In the western United States these blocks are made of concrete, have a specific gravity of about 2.3 in seawater, and are not particularly durable. In the eastern United States they are frequently fabricated using cinders or slag for aggregate and are known as cinder blocks. These are even less durable than the concrete block and have a very low specific gravity (about 1.5 to 2.0).

(1) Rubble Structures. Concrete blocks are frequently used for emergency protection because they are frequently readily available for only the cost of transporting. They generally break down through handling and are of no value in the armor layer or in the underlayer. They are not durable nor are they esthetically acceptable. However, they can be used as temporary protection during an emergency in isolated, nonrecreational areas as long as it is realized that they must be covered with designed layers of stone that will act as a protective material.

(2) Crushed Concrete Block. Concrete blocks will generally crush easier than broken concrete or stone and can be used in the same manner for bedding layers, filter layers, or as part of a base course for roads, parking lots, and storage areas.

c. Bricks. Common building bricks have a specific gravity of about 1.9. They are not generally durable when subject to abrasion nor are they esthetically desirable.

Salvage bricks may be rejects from the kilns or salvaged from dismantled buildings or structures. They may be a whole brick, a broken brick, or a cluster of bricks still bound by mortar.

(1) Rubble Structures. Salvaged brick is not desirable for either the armor layer or the underlayer of a breakwater, jetty, groin, or revetment due to its low specific gravity, lack of durability, and lack of esthetic appeal. It also tends to create slip planes. It may be used as core material as long as it is mixed with other materials and satisfies the general design criteria for core stone.

(2) Crushed Brick. When brick is crushed it may be used as base course material for roads, parking areas, and storage areas in the same manner as crushed stone. It has limited value as bedding material because of the low specific gravity and tendency to reduce to sand and clay sizes. It is of almost no value as a filter material because of lack of durability and a tendency to break down and fill the voids necessary for it to act as a filter material.

5. Salvaged Ships, Barges, Railroad Cars, Automobile Bodies, Refrigerators, and Others.

a. General. Because of their size and weight, it is always a temptation to use these no longer functioning objects to achieve "instant structures." In particular, some salvaged ships and barges might provide up to 300 meters (1000 feet) in length for a protective structure. Its weight may be several thousand tons. But there are difficulties involved in placement and perhaps even more difficulty in the task of removing these objects.

b. Salvaged Ships and Barges.

(1) Salvaged Ships. Salvaged ships are generally steel hulled, although there may be a few concrete-hulled ships from World War II, and they may be from 15 to 300 meters (50 to 1000 feet) in length. These ships are generally 20 to 50 years old and much of the internal equipment, particularly the heavy engines usually have been removed. The curved cross section of a typical ship's hull plus the partially streamlined bow and stern makes them difficult to place precisely and prevent shifting of position or capsizing. The general concept is to maneuver the ship into a predesignated location, sink it in place and fill it with sand, gravel, or rock to provide stability.

The steel hull plates of these ships originally vary from 6 to 19 millimeters (1/4 to 3/4 inch) in thickness, have already been exposed to 20 to 40 years of corrosion, and have a very limited life as a partially sunken ship. The plates can be subjected in shallow water to abrasion by the sand that is constantly in motion and the force of breaking storm waves in shallow water can be considerable. Once the hull opens up the disintegration of the ship can be very rapid and it will soon lose its effectiveness as a protective structure.

Even as a temporary protective structure if the ship settles too deeply into a sand bottom, rolls over, partially disintegrates, or is no longer floatable, it can be extremely difficult and costly to remove. It is obvious that as the ships disintegrate and are moved by waves or currents

they can become a hazard to navigation, a danger to recreationalists, and very unsightly from an esthetic point of view.

(2) Salvaged Barges. Barges may be of wood, steel or concrete. They are usually smaller than ships, more rectangular in dimension, and easier to place into position. They are usually flat bottomed and have a tendency to slide out of position under the force of storm waves. If positioned on sand, they are also subject to severe scouring action and may tilt or slide out of position. Like ships, they are usually many years old and seriously deteriorated before being salvaged. Wooden barges are the least desirable. They lack the deadweight of steel or concrete and once they start to disintegrate, the process is more rapid. Also, if filled with sand or gravel for stability they may even attain partial buoyancy as the waves remove this material.

Concrete barges are unsightly and dangerous due to the mass of reinforcing bars exposed as they deteriorate and break up. Steel barges, like ships, have relatively thin hull plates and through corrosion or wave forces deteriorate very rapidly, especially in seawater.

(3) Breakwaters and Jetties. Neither salvaged ships or barges are recommended for breakwater or jetty construction. Wave action is generally too severe and, in the case of breakwaters, the waves strike broadside, the most unstable position. Even for temporary or emergency protection, salvaged ships and barges are not recommended due to the difficulty of removal.

(4) Groins. There has been some limited success with the use of several barges in tandem. They must be securely fastened to each other and well seated on the bottom. Even so, because of deterioration, provisions must be made to either remove them or cover them with rock at a later date.

(5) Revetment. Salvaged ships or barges are not recommended for revetment. They are rigid structures and in an area of breaking waves will generate so much scouring action that more erosion may result than without these structues.

c. Salvaged Railroad Cars, Automobile Bodies, Refrigerators, and Others. These are used mostly for bank or shore protection in nonrecreational areas. They are all unsightly and, while made of metal, generally do not have much weight compared to total dimensions and are easily moved by waves or currents. Because of their rigidity and numerous flat surfaces they can cause accelerated scouring and may even accelerate the erosion process. Like other metals they are normally corroded before salvage and, if in seawater, the corrosion process is accelerated. Railroad cars and automobile bodies, in particular, will disintegrate within a few years. Their use is not recommended except in a nonrecreational area and only then as an emergency temporary measure, to be removed as soon as a long-term protective system can be implemented.

6. Rubber Tires.

a. General. About 2 million rubber tires, too worn for further use on trucks and automobiles, and not capable of being recapped or retreaded, are

available annually throughout the United States. While, as a material, rubber tires are strong and durable, they have almost no salvage value. Hence, they are generally available at very low cost or just for the cost of hauling. Rubber tires have been used for years as fenders on barges, work boats, and docks but it is only since about 1963 that they have been seriously considered as a low cost, and readily available, material for protection structures.

b. Characteristics. Salvaged rubber tires have a specific gravity of about 1.2. They are tough, flexible, durable and almost inert to chemical reaction in either fresh or salt water. In fact, the critical strength factor of a scrap rubber tire system is not the "tire" but the fastenings and the mooring system.

c. Uses.

(1) General. Salvaged rubber tires have been used primarily to form floating breakwaters but they also have potential use for revetments, groins, bottom stabilizers, and fishing reefs. Experiments are underway to use them as an additive to asphalt concrete paving.

(2) Floating Breakwater. Like all floating breakwater systems, the use of the floating rubber tire system is most successful where the need is to protect a basin area against short-period waves such as in bays, harbors, and lakes. Several different arrangements of tires have been used and model tested but the basic principles are the same.

(a) Flotation. Flotation is provided either by entrapped air or by the filling of a part of the tire with urethane foam. The air system works only for tires held in a vertical position. A regular schedule of adding air to replace lost air or compensate for added weight due to sea growth or the entrapment of silt must be established. Tires are bundled together in modules of a workable size and weight and then the modules are assembled into a floating breakwater of design length, width, and depth. Other design factors are the density of the tire assembly and the allowable load stresses on the fasteners and the mooring system.

(b) Fasteners. The scrap-tire assemblies have been secured by steel cable, galvanized iron chain, nylon rope, or (one of the most successful) scrap cuttings from conveyor belt material fastened together with nylon bolts, nuts and washers. The floating breakwater is a dynamic system, in constant motion, so it is imperative that an adequate inspection and maintenance schedule for these fastners and their hardware be established. Salvaged telephone or power poles may be used as inexpensive spreaders to frame the assemblage of scrap-tire modules. Poles and spreader framework may be specially treated to extend the useful life of fasteners; however, in view of the low-cost aspect of salvage systems generally this expense may not be justified.

(c) Moorings. Standard mooring systems of steel cable or galvanized iron chain with anchors or anchor blocks are generally used to hold the breakwater units in place. Mooring stresses will depend on wave forces, density of the tire modules, width of the system, and depth of the

water as related to the depth of the floating breakwater system. As with fasteners, a prudent inspection and maintenance schedule is mandatory.

(3) Revetments. If the tires or modules of tires can be securely anchored to the bottom of the natural slope they can serve as revetments. With a specific gravity of only 1.2 they cannot be expected to stay in place of their own weight. They do not act as a revetment in the same manner as rock rubble; i.e., by completely absorbing or reflecting wave energy before it reaches the native bank material. The rubber tire revetment will only partially reduce the energy of the waves and, under persistant attack, increased turbulence may even accelerate the erosion of the native material. It may be feasible to use the rubber tires in conjunction with underlayers of rock to act as a revetment, providing the tires are securely anchored in place.

(4) Bottom Stabilizers. Rubber tires are being used in parts of the Chesapeake Bay where waves are small and erosion is slow or intermittent; they apparently function by encouraging the growth of marsh grasses and the resultant increase in an accumulation of mud to stabilize the entire mass.

Some success in use of tires to control littoral drift has been reported in areas of low turbulence by simply anchoring rubber tires to the seabed to slow the bedload movement of sand either by currents or wave-induced movements in the littoral zone. This is obviously not feasible in the breaker zone of the open coast and the entrapment of sand outside the breaker zone would be slow and of minor quantities. This application may have particular merit in lakes, reservoirs or bays where surf is not severe.

(5) Fishing Reefs. Modules of rubber tires, placed in deep water will, because of added surface and the many voids and crevasses, encourage the growth of marine plants and animals. The modules must be anchored in place but this is not as difficult as when used for floating breakwaters or revetments.

7. Uses in Coastal Construction.

a. General. The use of recycled materials is very sensitive to the degree of emergency or lack of availability of new materials, the availability of the recycled materials, and the suitability of the materials to accomplish the desired design objectives. In some cases such as floating breakwaters, the recycled material, in this case rubber tires, may actually be the preferred material. In every case, the conditions peculiar to the project determine the usability of recycled materials. When suitable, recycled materials can be used in the following types of coastal structures.

b. Offshore Structures.

(1) Breakwaters. Concrete rubble and salvaged asphaltic concrete can be used as a substitute for stone underlayers or cores but their lower densities must be considered when making the substitution. Crushed concrete can be an effective core material. Concrete blocks and brick can also be used as rubble in place of stone underlayer or core allowing for their lower densities. Crushed, these materials can be used for core material.

Rubber tires are used to make floating breakwaters capable of attenuating short-period waves. Salvaged ships and barges should not be used as breakwaters in the ocean or large lakes and have limited use as a type of caisson in that they are generally located at a remote station and towed to the site where they are sunk and perhaps filled with sand or rock to serve as breakwaters or reefs.

(2) Reefs. In addition to barges, automobile and railroad car bodies, broken concrete and rubber tires can be formed to trap sand for beach contouring and to encourage the growth of marine biota. Broken asphaltic cement, concrete blocks and bricks can all be used to create rubble-mound reefs. Below the wave and breaker zone such materials are more durable and more likely to serve successfully.

c. Shore-Connected Structures.

(1) Breakwaters, Jetties, and Groins. Salvaged concrete, broken asphalt cement, concrete blocks, bricks, salvaged ships and barges, salvaged railroad car bodies, and automobiles can be used as discussed for offshore structures but they all have severe limitations.

(2) Seawalls and Bulkheads. Toe protection and backfill materials, where rock would normally be used, can be of salvaged concrete, asphaltic cement, concrete blocks or brick. These materials could also serve as aggregate for preplaced aggregate concrete.

(3) Revetments. All the materials discussed in this section except the ships, barges and car bodies can be used to stabilize revetments. The finer particles of crushed materials would be suitable for filter blankets, the rest as rubble or cover material.

(4) Piers and Wharves. Salvaged rubber tires make good bumpers and fenders for small craft using the piers and wharves. Tires are also good buffers between independent floats or structures that might otherwise bump or scuff each other in moving with tides, waves or currents.

Broken concrete, asphaltic concrete and broken concrete blocks or bricks can be used as revetment to protect the shoreside embankment of piers or wharves.

XI. PROTECTIVE SYSTEMS FOR MATERIALS

1. Corrosion.

a. General. To understand the reason for using coatings or applying cathodic protection, a brief review of corrosion fundamentals is necessary. These principles apply to any metal structure. Corrosion is defined as the deterioration of a material, usually a metal, or of its properties because of a reaction with its environment. Three conditions are necessary for metallic corrosion to occur:

(1) There must be an electrical potential difference between two metallic electrodes, anode and cathode. This can exist because of metallic composition differences, metallic surface condition differences, or because of differences in the environment contacting the electrodes;

(2) the contacting environment (electrolyte) must be electrically conductive with positively and negatively charged ions present; and

(3) there must be a metallic connection between the electrodes.

b. Corrosion Process. Corrosion is a natural process involving electrochemical reactions with a resulting flow of direct current from anodic areas of the substructure (corroding areas) to cathodic areas of the substructure, through the surrounding and contacting electrolyte (soil or water environment). A simplified diagram of the corrosion process on iron or steel in water is shown in Figure 90. The circuit is completed through the metallic connection between anode and cathode. They both may be part of the same structure. This current flow is called galvanic current and usually is in microampere or milliampere quantities. With steel substructures, corrosion (loss of metal) takes place only at anodic areas as the result of current flow into the electrolyte from anodic areas. In the case of iron or steel, metal loss amounts to about 90 newtons (20 pounds) per ampere-year of current flowing from the metal into the contacting electrolyte. Loss of metal is directly proportional to the amount of current. One milliampere of current leaving the substructure from one point into the electrolyte will cause penetration of 9.5 millimeters (3/8 inch) steelplate in less than 1 year. See Table 40 for corrosion rates of other metals, including anode materials. With iron or steel substructure the electrochemical reaction prevents corrosion of areas where current flows from the electrolyte into cathodic areas of the substructure. Anodes, cathodes, and corrosion current as related to steel in water are shown in Figure 91.

c. Corrosivity of the Environment. In air the corrosivity of the environment on a structure will depend on the temperature (ranges and mean averages), relative humidity, wind conditions, proximity to the water, rainfall, and chemical fumes (from cargo or nearby plants). Corrosivity generally increases with increases in temperature, relative humidity, wind velocity (particularly off water); with closeness to the water; with increased rainfall; and with higher concentrations of chemical fumes.

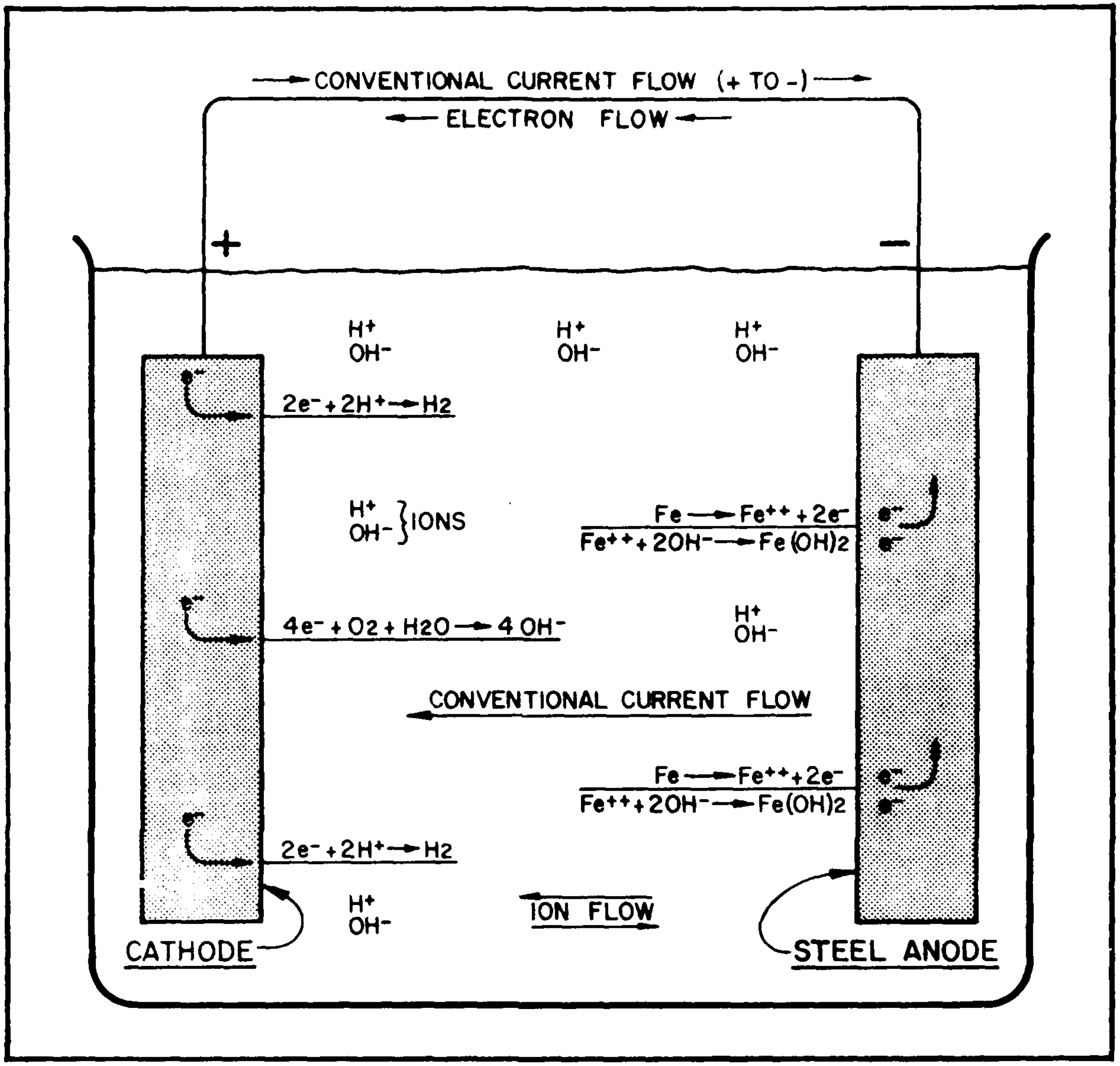


Figure 90. Corrosion process.

If the structure is to be immersed, the corrosivity will depend on the temperature of the water, chemical composition (salt content, dissolved oxygen and the presence of other chemicals), velocity of the water (movement by tides, waves, gravity, etc.), and splash zone effects (a combination of mechanical and corrosive effects). Corrosivity on immersed or partially immersed structures generally increases with increases in temperature, increases in corrosive chemical content, increases in fluid velocity and in the splash zone. It should be noted that high purity water such as distilled water or deionized water is a special condition and can cause coating to blister or delaminate.

Table 40. Corrosion rate of some common metals.

Metal	Consumption Rate (newtons per ampere-year)
Lead	333.6
Copper	204.6
Tin	191.3
Zinc[1]	102.3
Iron	89.0
Magnesium[1]	75.6
Aluminum [1]	26.7 (seawater)
Carbon[1]	8.9
High Silicon Iron[2]	less than 0.44
Magnetite Fe_3O_4[2]	less than 0.044 5
Lead-Silver[2]	less than 0.044 5 (seawater)
Platinized Titanium[2]	less than 0.000 044 (seawater)

[1]Galvanic anode material
[2]Impressed current anode material

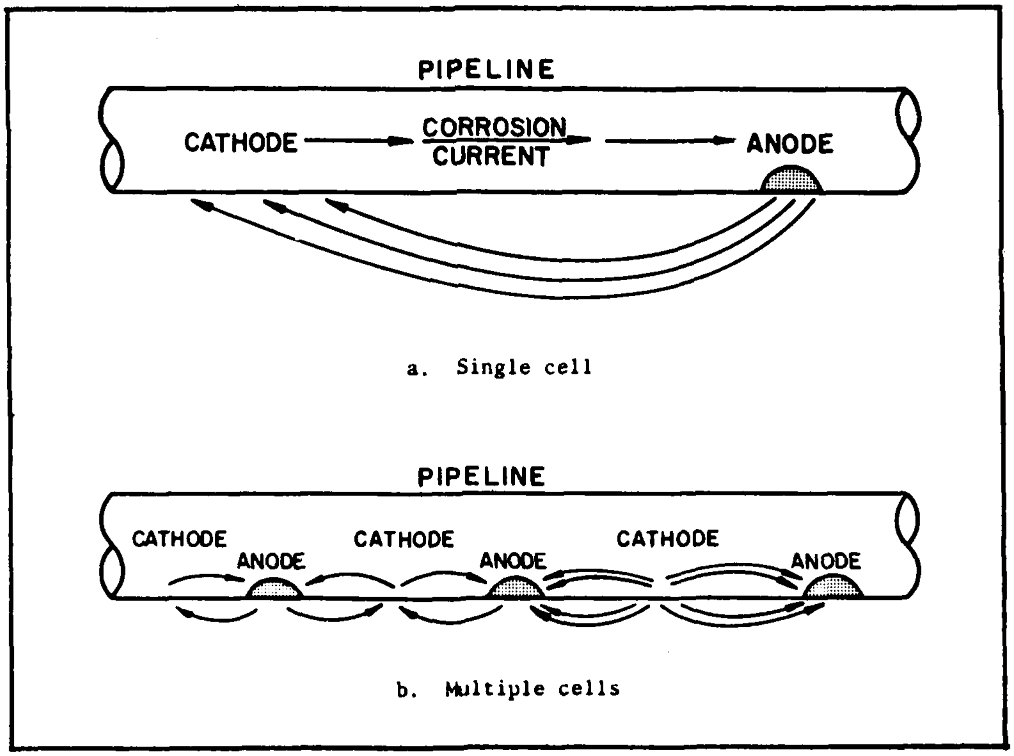


Figure 91. Corrosion process in pipelines.

d. Corrosion Prevention. The corrosion process on a given structure can be prevented or stopped if any one of the three conditions necessary for corrosion can be eliminated. The principal methods for preventing or mitigating corrosion are described below.

(1) Coatings. A perfect coating will electrically insulate the anode and cathode areas from contact with the electrolyte, preventing flow of corrosion current. As is well known, a perfect coating is an impossibility for anything other than a laboratory-scale project. Also, all coatings disintegrate in time, imposing an ever-increasing area of poorly coated or bare metal. Cathodic protection is an ideal way to deal with coating discontinuities (holidays) and poor coating in general. Coatings (with cathodic protection) are feasible for practically any subsurface structure. An exception would be the underwater parts of offshore oil production platforms where coating repair or replacement would not be possible.

(2) Insulated Joints. Insulating joints between metal plates or piping joints will minimize stray current or galvanic corrosion where it interrupts corrosion current flow. In this application, the metallic connection between widely separated anode and cathode areas is broken by the insulating joint. Insulated joints also serve to separate dissimilar metal areas, as well as to separate cathodically protected areas from unprotected areas.

(3) Cathodic Protection. The corrosion process on a given subsurface structure can be prevented or stopped by supplying an excess of electrons to all subsurface parts of the structure. The result is that the structure becomes all cathode because of the electrons provided by forcing direct current to flow through the contacting electrolyte (water or soil), from a nearby subsurface source (anode) onto all subsurface parts of the structure. Hence the name, cathodic protection. When the current is adjusted properly, it will counteract corrosion current flowing into the electrolyte from the substructure with an opposing and slightly more than equal flow of current flowing from the electrolyte into the substructure. Loss of metal has been transferred from the protected substructure to the external anode which will require occasional replacement.

2. Coatings.

a. Introduction. Environmental conditions affecting coastal structures range from mild to severely corrosive. To provide suitable service life for coastal structures, protective coatings are usually required, ranging from little or none (other than decorative painting) to complex and extensive multicoat systems. Specific coating demands depend upon type of substrate to be coated and its environment.

This section will cover the basic design considerations that must be given to the structures to be protected and to the selection, application and inspection procedures necessary to provide a protective coating system with years of dependable service life. Repair, rehabilitation, proper maintenance procedures and other important facets, including economics, are also described.

Protective coatings are designed primarily to isolate metal surfaces from exposure to corrosive elements. Coating thickness will vary from 50 to 75 micrometers (2 to 3 mils) for simple alkyd coating systems to 380 to 760 micrometers (15 to 30 mils) for certain high build coal tars, coal-tar epoxies or urethanes (1 mil equals 25.4 micrometers or 0.025 millimeter; where any conversion in a discussion results in numbers less than 0.1, micrometers will be used).

Conventional paints, surface preparation and methods of application should not be used in corrosive areas of coastal structures. Only high performance protection coatings such as epoxies, zinc rich, chlorinated rubber, and polyurethanes must be considered. Products selected for use should be resistant to the environment and capable of serving as a barrier between the environment and the substrate. Writing appropriate specifications to cover all facets of the work will play an important role in terms of obtaining the protective coating job desired including, particularly, cost per unit area per year of service life.

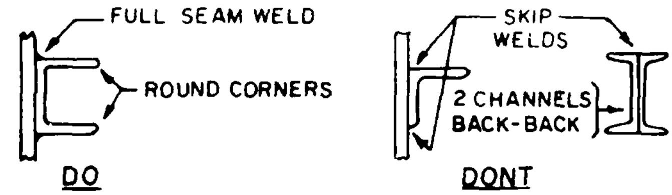
b. Design and Specifications. In the design of new structures, it is important to consider surface requirements for ease of coating application and effectiveness of coating. The design should (1) provide smooth, flat, easily curved surfaces, and (2) avoid overlapping surfaces, edges, back-to-back structures (brackets, beams or L's), riveted surfaces, sharp protrusions, and weld splatter (see Fig. 92).

Like other personnel in any design and construction organization who are engaged in translating an owners requirement into design and the design into a structure, the protective coating specifier must give careful consideration to all aspects of the coating work requirements. The specification must detail coating selection, surface preparation, coating application, coating inspection, touchup, and repair to ensure a successful job.

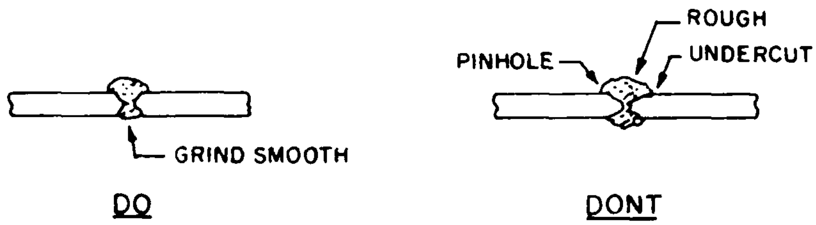
c. Generic Classes. Numerous coastal marine coating tests and surveys of field applications have been made. Table 41 lists some of the coating systems used for various surface substrates. In the discussion which follows, various uses and precautions are presented for each coating system, with a brief description of chemical composition and properties.

Coatings are composed of many raw materials. These materials can be divided into three categories--vehicle, pigment, and additives as shown in Table 42. The vehicle or liquid part of a coating is composed of resin, solvent, and plasticiser. The vehicle resin contributes to many of the basic properites of a coating including water resistance, chemical resistance, cure time, elongation, toughness, and adhesion to substrate.

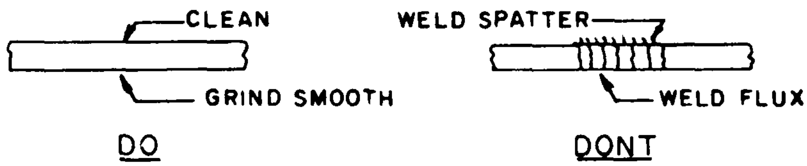
SPECIFICATION CONSIDERATIONS



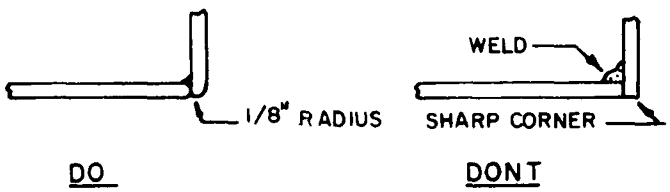
POCKETS OR CREVICES. ALL CONSTRUCTION INVOLVING POCKETS OR CREVICES THAT WILL NOT DRAIN OR THAT CANNOT BE PROPERLY BLAST-CLEANED SHOULD BE AVOIDED.



CONTINUOUSLY WELDED JOINTS. ALL WELDED JOINTS SHOULD BE CONTINUOUSLY WELDED. ALL WELDS SHOULD BE SMOOTH, WITH NO POROSITY, HOLES, HIGH SPOTS, LUMPS OR POCKETS. GRINDING SHOULD BE USED TO ELIMINATE POROSITY, SHARP EDGES AND HIGH SPOTS THAT DO OCCUR.



REMOVE WELD SPATTER. ALL WELD SPATTER SHOULD BE REMOVED.



MINIMUM RADIUS OR CORNERS. ALL SHARP EDGES SHOULD BE GROUND TO A MINIMUM RADIUS OF 1/8" (3.2 mm).

Figure 92. Examples of design details to aid coating application.

Table 41. Types of coatings commonly used on different substrates.

Substrate	Paint	Comments
Interior Wood	Oil	Generally slow drying and relatively soft.
	Alkyd	May be hard or soft.
	Latex (Vinyl or Acrylic)	Can be applied over oil, alkyd, or latex primer.
Exterior Wood	Oil	Good wetting of weathered wood and paint chalk; slow drying; soft.
	Alkyd	Good wetting; variations give variety of properties.
	Silicon Alkyd	Good wetting; good gloss.
	Latex (Vinyl or Acrylic)	Poor wetting of weathered wood and paint chalk; easily applied.
Interior Masonry, Plaster, and Wall Board	Acrylic Latex	Easily applied; brushing is good on coarse surfaces; must remove all loose chalk.
	Vinyl Latex	Same as Acrylic Latex.
	Chlorinated Rubber	Good for waterproofing,
Exterior Concrete, and Masonry	Acrylic Latex	Fill coats of these materials will reduce water penetration.
	Vinyl Latex	Same as Acrylic Latex.
	Chlorinated Rubber	Good for waterproofing.
	Vinyl.	For concrete in very corrosive environments.
Interior Iron and Steel	Alkyd	Never on continuously damp or immersed environments.
	Vinyl	Good resistance to water, poor to strong solvents.
	Epoxy	Good durability and chemical resistance.
	Urethane	Good durability and chemical resistance.
Exterior Iron and Steel	Oil	For mild environment only,
	Alkyd	For mild environment only.
	Silicone Alkyd	For mild environments only; good gloss.
	Inorganic Zinc	Very abrasion resistant; limited life in seawater without topcoat.
	Vinyl	Good durability; easily touched up.
	Epoxy	Good durability and chemical resistance, but chalks in sunlight
	Urethane	Aliphatic type has good weathering over epoxy primer.
	Chlorinated Rubber	Good ductility and fair corrosion resistance

Table 42. Coating components.

VEHICLE				
RESIN	PLASTICISER	SOLVENT	PIGMENT	ADDITIVES
Alkyd	Glycols	Prime Dilutents	Prime Extenders	Surfactants Drying Agents
Epoxy			Color	
Coal Tar		Mineral Spirits	Corrosion Inhibitor	Anti-Skinning Agents
Vinyl		MEK Toluene		
Other				

Coatings are usually named or designated by their resin systems. For example, an alkyd coating contains an alkyd resin, an epoxy coating contains an epoxy resin, and a silicone alkyd contains an alkyd resin as the primary resin system with additions of silicone resins. Plasticisers are added for modifying the properties of the resin. Solvents are used for dissolving or dispersing the resin for manufacture. Solvents are also useful for developing and controlling application properties of a coating. For example in a cold climate, the solvent must be volatile enough to evaporate at low temperatures. Conversely, in tropic or desert climates, the solvent must be slow enough (less volatile) to allow the coating to flow out and properly cover the hot surface before it volatilizes.

The pigments are the finely ground solids which are added to give coating body, color, and corrosion-inhibitive properties. Special additives are added, usually in small amounts, to give the coatings many special properties.

Table 43 lists generic coating types suitable for use on concrete and steel (both immersed and nonimmersed). Selection of a recommended coating system for a given service condition is determined from specific properties of coating types, described below.

(1) Alkyds. Alkyds are formed when oil is combined chemically with glycerol phthalate. They cure by reaction with oxygen and have excellent wetting properties and fair to good weather resistance. Alkyds have poor resistance to acids and alkalies and only fair abrasion resistance. They should be used only for mild environments in selected harbor locations. They should not to be used where surfaces are continuously damp or immersed in water.

(2) Silicone Alkyd. Silicone alkyds possess properties similar to alkyds as defined above but possess somewhat better heat resistance, weather resistance, and gloss retention. They cannot be used for immersion. Also they are softer and are less resistant to abrasion.

Table 43. Recommended coating systems.

Type of Surface	Coating Type
Concrete	Coal Tar
	Coal-Tar Epoxy
	Epoxy
Steel (Nonimmersed)	Alkyd
	Silicone Alkyd
	Silicone Acrylic
	Coal Tar (Good)
	Coal-Tar Epoxy (Good-Excellent)
	Epoxy (Good-Excellent)
	Urethane (Good-Excellent)
	Vinyl
	Zinc Rich
Steel (Immersed)	Coal Tar
	Coal-tar Epoxy
	Epoxy
	Epoxy Phenolic
	Phenolic
	Vinyl

(3) Modified Alkyds. Modified alkyds have additional resins added (such as ester gum, phenolic, styrene, vinyl, acrylic and chlorinated rubber) to improve properties such as weather resistance and corrosion resistance. They may be used for some coastal structures, however, because of the limited corrosion resistance of alkyds, immersion service or exposure to corrosive environments is not recommended.

(4) Acrylic (Solvent Base). Acrylic coatings may be formulated as solvent-base or as water-base materials. The solvent-base coatings are composed of copolymer acrylic resins in an aliphatic hydrocarbon solvent. They cure by evaporation of solvents and in some respects possess the toughness and corrosion resistance of a baked enamel. Acrylics have good resistance to general weathering. They have excellent gloss retention and color stability. Their resistance to marine atmospheres and corrosive environments is good. They have good impact resistance and fair heat resistance. Acrylics may be used as topcoats for epoxy, modified alkyd, zinc rich and universal primer. They are not recommended for immersion.

(5) Acrylic (Water Base). The water-based acrylic products are widely used for masonry, stucco, or wood for both interior or exterior application. They are also used to a limited extent for metals. Because they are water based they are nonflammable and may be used in fire hazard areas. They are quick drying and may be easily cleaned with water. Acrylic water-base coatings have excellent color retention, good flexibility and toughness, and are easy to repair. They have only fair corrosion resistance.

Acrylic resins are used in conjunction with other resins to improve color stability and general weathering resistance.

(6) Chlorinated Rubber. Chlorinated rubber coatings are composed of rubber polymers chemically treated with chlorine in a blend of solvents. They cure rapidly by solvent evaporation. Chlorinated rubber coatings have fair to good corrosion resistance to marine and chemical corrosion. They resist most dilute acids, alkalies and salts and have fair weathering resistance and color stability. They are suitable for immersion in salt and fresh water to 49° Celsius (120° Fahrenheit). Chlorinated rubber coatings have fair abrasion and impact resistance but possess only poor resistance to organic solvents.

(7) Coal-Tar Coatings.

(a) Mastics and Coal-Tar Cutbacks. Coal tar is a byproduct of the coal coke industry and has outstanding water resistance. For this reason it has been found to be an excellent coating material for use on many coastal structures. Its high resistance to moisture makes it useful for immersion or for the splash zone service. It is one of the finest coating materials for resistance to water or moisture. For this reason, it is frequently used for protecting steel or concrete in immersion. Coal-tar products are usually applied by spray because of their heavy consistency, but touchup is frequently handled by brush. Additional thinner may be added when the coating is applied by brush.

(b) Modified Coal-Tar Coatings. Coal-tar coatings are frequently modified with other materials such as epoxy or polyurethane. The modified products have the excellent water resistance of the coal tar with the improved toughness and solvent resistance of the modifier. Properties of coal tar and the modified materials are as follows:

(1) Coal-tar properties: low cost, excellent resistance to water, low moisture vapor transmission, poor resistance to organic solvents, and poor abrasion resistance and toughness;

(2) epoxy properties: tough, chemical resistance, and solvent resistance; and

(3) urethane properties: elastomeric and abrasion resistance.

Two component coal-tar epoxy and coal-tar urethane coatings are discussed. Coal-tar epoxy systems contain coal tar, pigments, solvents, epoxy resin, and either an aliphatic or aromatic amine or polyamide curing agent. Coal-tar urethanes contain coal tar, pigments, solvent and reactive urethanes. These "chemically cured" coal-tar coatings can be applied in one coat to dry film of 0.13 to 0.64 millimeter (5 to 25 mils). Most coal-tar epoxies have excellent adhesion, abrasion, and impact resistance. Their resistance to immersion effects in salt and fresh water is excellent and they withstand a wide range of chemical corrodents. Proper measurement of two components is mandatory for proper cure and coating properties. It is recommended that these coatings be mixed by use of power mixers. Subsequent coatings must be applied within manufacturers' specified time and temperature limitations to avoid delaminization between coats. The coal-tar epoxies have a variable pot life when mixed depending on the temperature. Repairability is a major problem and color is limited to black. They tend to chalk lightly in sunlight and weather and lose their original black gloss within 6 months to 1 year.

(8) Epoxies (Catalyzed). Epoxy coatings are based on epoxy resins and are supplied as two component materials. One component contains the epoxy resin, the other the curing agent. The two components must be thoroughly mixed before application. A broad spectrum of service conditions is covered by a wide variety of materials based on these versatile resins. Amine or polyamide type curing agents are most common. Epoxies have excellent durability and toughness and possess high chemical and moisture resistance. They resist strong alkali, and have excellent adhesion properties and abrasion resistance. They may be used in marine environments and are not damaged by moisture or immersion in water.

Epoxies may be used in conjunction with special fillers to make mastic-like materials which find applications as concrete grouts, surfacers or "bug hole" fillers. These mastics or grouting compounds may be applied as heavy coats by trowel or in some cases by spray. They are used in marine application to protect concrete or steel in the splash zone. Heavy layers of the mastic are built up in the splash and tidal zone. Layers of glass fabric may be introduced, between coats of mastic to add strength to the splash zone coating system. Application is sometimes by hand in a process

known as "palming" (Fig. 93). Gloves should be worn when handling epoxy materials as many people have a toxic reaction to epoxies.

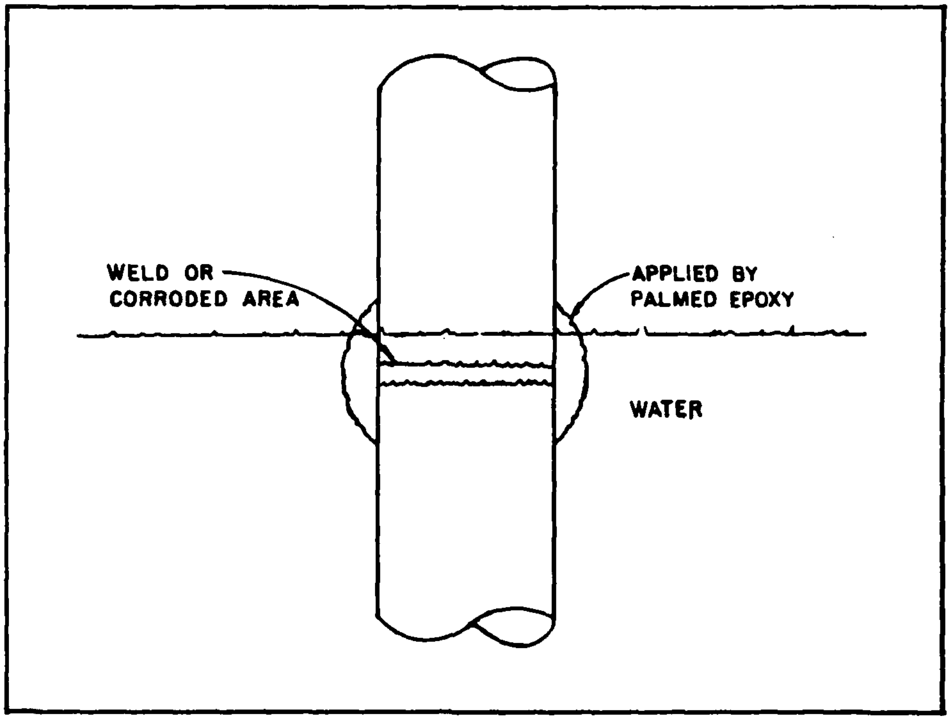


Figure 93. "Palmed" application of epoxy underwater coating.

Certain epoxy polyamide coatings and mastics will cure on moist surfaces, or even under water. It is this property that allows these materials to be utilized for coating and for repairing wet or submerged structures which require protection. Epoxy coatings have excellent corrosion resistance to most chemicals. They perform well in alkaline media but are only fair in contact with acids. Because of their inertness they are sometimes difficult to repair or topcoat. Because of adhesion problems, very few coating materials will adhere to a well-cured epoxy. Epoxy coatings tend to chalk and for this reason, colors fade, particularly dark colors. The lighter colors are most frequently specified for use where the coating will be exposed to sunlight and weather. To summarize, epoxy coatings have excellent corrosion resistance and toughness, but are fair to poor in weather resistance.

(9) Epoxy Phenolic. Epoxy phenolic coatings are epoxy-type coatings which have been modified by the addition of phenolic resins. The phenolic resin adds corrosion resistance as it promotes cross linking and bonding of the epoxy resin as illustrated in Figure 94.

With the increased resistance of the epoxy phenolic coatings to attack by corrosive chemicals or environments, these materials find application as linings for tanks, barges, ships, and piping.

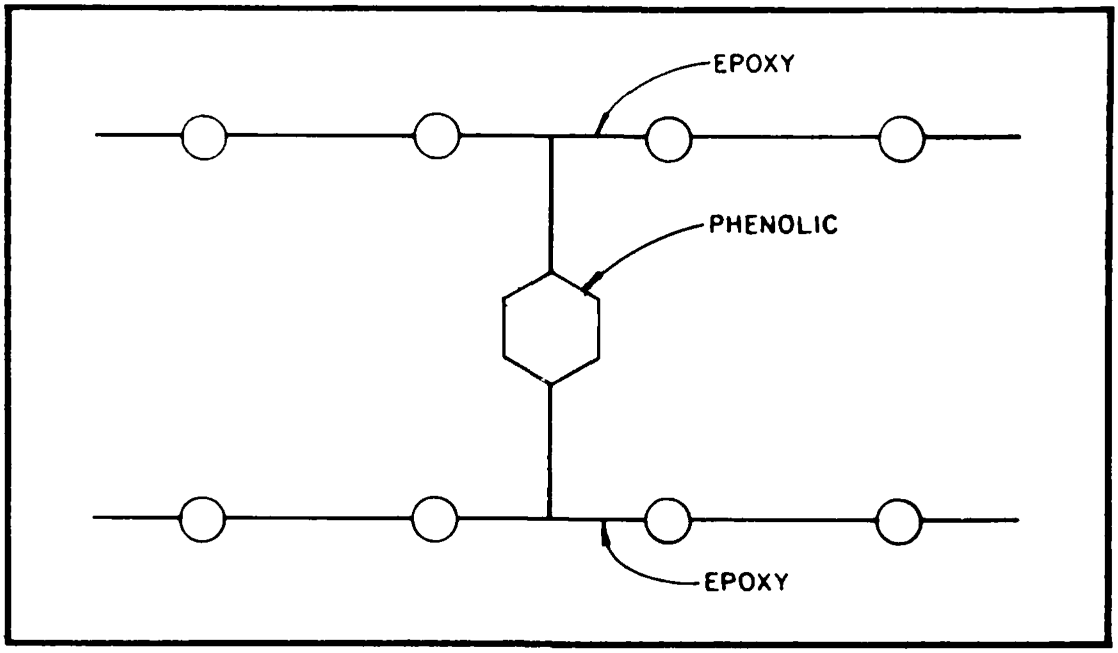


Figure 94. Cross-linked epoxy phenolic.

The disadvantages of epoxy phenolics, as compared to epoxies are:

(a) Increased brittleness of coating;

(b) lack of toughness and thus more subject to damage upon impact (cracking, shattering, delamination);

(c) requirement for heat in curing (not true with all epoxy phenolics);

(d) lack of availability in high build formulations; and

(e) slightly more difficult to repair and topcoat due to adhesion problems {see paragraph (8)}.

(10) Phenolics. Phenolic coatings include baking phenolics of the alcohol soluble type and phenolics of the oil soluble type in combination with drying oils. The baking phenolics have excellent resistance to corrosive chemicals, acids and caustics. They require baking for curing (cross linking). The baking phenolics form tightly cross-linked coating films with exceptionally high corrosion resistance, which is higher than the epoxy-phenolics. Because of their tight cross linking they are brittle and subject to damage and delamination if subject to impact. These materials are used as linings for tanks, barges, and piping.

The phenolic coatings designed for atmospheric service are made from phenolic resin combinations and drying oils. These, at one time, were considered the best air-drying coatings for water resistance and weak chemical resistance; they were used extensively as marine maintenance coatings. They are still considered superior to most alkyd coatings in

hardness, abrasion resistance, and chemical resistance. Their limitations include somewhat less weather resistance than certain alkyd coatings. They possess only fair gloss retention and are applied at comparatively low film thicknesses. They also require good surface preparation for best performance. Many phenolics become brittle with age.

(11) Polyurethanes. These generic class products, more commonly called "urethanes," are usually comprised of either moisture-cured, single-packaged systems, one single package which requires heat to cure, or two-packaged catalyst-cured types. All urethanes contain isocyanate. The single package systems include one which cures by reaction with moisture and one which is cured by heat. The two-packaged systems are cured by reaction with a curing agent such as an hydroxl-bearing polyols.

Due to the wide variety of formulations available, the selection of the proper urethane for a specific job is often difficult. Chemical resistance (fumes, splashes, and spills), especially with those cured by hydroxl-bearing polyols, is very good. Others may be somewhat limited in this respect. These type coatings are best known for their toughness and resistance to abrasion and impact. The urethanes based on an aliphatic resin possess outstanding resistance to sunlight and weather including excellent gloss retention. These are used extensively on ships and aircraft where color retention is important. Other urethane formulations based on aromatic urethane resins have poor weather resistance. They should not be used as exterior coatings.

Adhesion properties are fairly good to properly primed metal or direct to masonry. Urethanes also adhere generally well when directly applied to fiberglass materials. There are some formulations which have high build properties. Many urethanes have excellent low temperature cure characteristics and may be used at temperatures as low as 2° Celsius (35° Fahrenheit). Urethanes have excellent flexibility and elongation properties. Because of the inertness of the two component polyurethanes, repairability and recoating can be difficult due to adhesion problems.

(12) Vinyls. This class includes all polymers and copolymers of vinyl chloride with vinyl acetate and vinylidene chloride. They are single-packaged coatings and cure by solvent evaporation. Vinyls are also processed with oil base materials such as alkyds, phenolics, and acrylics. Most offer good overall corrosion resistance. They are somewhat similar in this respect to chlorinated rubber.

Vinyls withstand high humidity and are comparable to epoxies in many respects in resistance to salt atmospheres and immersion in water. They have good abrasion and impact resistance. Flexibility and elongation properties of vinyl coatings are good. Vinyls are among the best coatings from standpoint of resistance to oxidation. Many have good gloss retention. Their repairability is very good, and they usually present very few problems on recoating. Resistant to most solvents, however, is poor and they have a limited heat resistance.

(13) Inorganic Zinc. These products are formulated with metallic zinc dust, at relatively high pigment volume concentration, with inorganic binders. Metallic zinc content is 60 to 90 percent by volume in the dried

film. As a single coat system they have outstanding corrosion resistance on coastal structures for protecting metal exposed to aggressive marine atmospheres. They may be topcoated to produce a coating system with an even greater anticipated service life. Inorganic zinc coatings may also be used in industrial environments. In [illegible]
be used without topcoat [illegible]
the past, is lining hydrocarbon tanks, both on barges and [illegible]

Inorganic zinc has excellent abrasion resistance and is often used as preconstruction primer. It must be topcoated for use in aqueous immersion. Zinc coatings offer excellent resistance in the splash zone to saltwater and to freshwater. Zinc-rich primers are often used as primers for organic topcoats such as chlorinated rubber, vinyls, epoxies, urethanes, and certain acrylics in more aggressive chemical atmospheres [illegible] also be topcoated for continuous immersion in water. Surface preparation requirement is stringent and application requires skilled workers.

(14) Organic Zinc. This classification of coating is composed of zinc dust with organic binders such as epoxy resins. Zinc dust content will vary between 45 and 80 percent by volume in the dry film. Performance of the coating is related to the percentage of zinc in the final dry film. Generally, the more metallic the zinc, the better the performance. Organic zinc coatings also show excellent resistance to high humidity splash and spray conditions of both fresh and salt water. Abrasion resistance is somewhat less than the inorganic zinc primers. The organic coatings will tolerate mildly alkaline atmospheres. They are often preferred to "inorganic" zinc as primer for chemical atmospheres because surface preparation and application procedures are less critical.

(15) Underwater Curing Coatings and Mastics. These materials are two-component 100 percent solids polyamide cured epoxy nonshrinking compounds (sometimes combined with appropriate fillers), designed to chemically displace water on the surface and form a tight bond. Extensive and careful laboratory and field tests, combined with experience information, have shown that good protection can be provided to in-place underwater structures with these mastics.

They are applied by gloved hand (palming) or trowel to a dry film thickness of 3.2 to 6.4 millimeters (125 to 250 mils), and cure while under water after several days. Tensile strength, adhesion, impact strength and abrasion resistance are fair to good. They can be used as patching compounds to seal metal, concrete, wood, fiberglass and many other substrates specifically in situations where the surface is damp, wet, or under water. The surface preparation recommended is sandblasting for best results. Costs of material and application are very high, $54 to $162 per square meter ($5 to $15 per square foot).

(16) Other. There are other special coatings that may be used from time to time for certain applications for coastal structures. These materials are combinations and modifications of the above generic coating classes. They will not be discussed in detail in this report. These coatings include vinyl polyurethanes, epoxy/fiber reinforced mortars and coatings, polyester/glass flake combinations, glass flake/coal tar/epoxy, 100 percent solids urethane/elastomeric membranes, catalyzed hypalon/coal

Table 44. Qualities of various coatings.

	Gloss and Color Retention	Resistance To								Time to Handle	Cost
				Moisture		Chemical Attack					
		Abrasion	Weather	Condensation	Immersion	Acid	Alkali	Aliphatic	Aromatic		
1. Alkyds	F	P	F-G	F	P	P	P	F	P	F-P	Low
2. Silicone Alkyds	G-E	P	G-E	F	P	P	P	F	P	F-P	Medium
3. Chlorinated Rubber	F	F-G	F-G	E	E	G	G-E	F	P	F-G	Low-Medium
4. Coal-Tar Coatings	F	F	F	E	E	G	F	F	P	F	Low
5. Coal-Tar Epoxies	F	G	F	E	E	G-E	E	G	F	F	Medium
6. Epoxies	P	G-E	F-G	E	E	G	E	E	G	F	Medium
7. Epoxy Phenolics	P	F-G	F	E	E	F-G	F	E	E	F	Medium-High
8. Phenolics	F	F	F-G	E	E	F-G	F	E	E	F	Medium-High
9. Polyurethanes	E	E	E	G	F-G	F-G	F-G	G	G	G	High
10. Vinyls	G	G	G	G-E	E	E	G-E	G	P	F-G	Medium
11. Zinc-Rich Coatings	NA	E	E	E	F-P	P	P	E	E	E	High

E = Excellent G = Good F = Fair P = Poor NA = Not Applicable

tar and others. Table 44 compares the qualities of various types of coatings.

d. Surface Preparation.

(1) Methods and Limitations. Proper preparation of the surface to receive the coating may be the most important activity in a coating job. Regardless of the chemical and physical properties of a coating (such as chemical resistance, moisture resistance, impermeability, abrasion resistance and weather resistance), it cannot properly fulfill its function unless it adheres to the substrate. Proper surface preparation consists of preparing the surface to the proper degree of cleanliness and roughness (surface profile) to receive a specific coating. There are a number of methods used for cleaning and roughening a surface.

Coatings designed for usage in corrosive environments have been found to give best performance when applied to clean, freshly blasted surfaces. The more resistance or durability expected of a coating system, the better the surface preparation must be. The better surface preparation, the better the performance. Methods of surface preparation have been defined and described by the Steel Structures Painting Council (SSPC) (1975), and by the National Association of Corrosion Engineers (NACE) (1979) of Houston, Texas.

Methods of cleaning include hand cleaning with brushes, mechanically cleaning with brushes, and blast cleaning with abrasives. Hand and mechanical cleaning procedures are defined and described by SSPC specifications: SSPC-SP-2, Hand Cleaning, and SSPC-SP-3, Mechanical Cleaning. These procedures are usually carried out by using wire brushes.

Blast cleaning procedures are the preferred method of cleaning as they provide surface roughness (surface profile) as well as cleaning the surface. These procedures, described and defined by the SSPC and NACE, are based on the degree of cleanliness of the surface. All loose surface contamination must be removed. The percent of firmly adhering residues allowed to remain are indicated in Table 45.

Table 45. Residues permitted to remain on blast-cleaned surfaces.

Surface Preparation		Degree of Cleanliness	Firmly Adhering Material Remaining on Surface (pct)
SSPC-SP	NACE		
5	1	White Metal	0
10	2	Near White	5
6	3	Commercial	33.3
7	4	Brush Blast	na

(2) Immersed Zones. For immersed zones or areas of severe chemical exposures, the surface preparation recommended is "white" metal (SSPC-SP-5; NACE-1). Near white (SSPC-SP-10; NACE-2) is sometimes specified for these same applications but is not as satisfactory and the life expectancy of the coating system will be decreased. The near-white surface preparation blast

clean is usually reserved for slightly less corrosive exposures such as nonimmersion marine. Commercial blast-cleaning surface preparation (SSPC-SP-6 or NACE-3) is utilized for still less corrosive exposures such as mild marine or industrial exposure. Table 46 shows recommended surface preparation for maximum results with specific generic classes of coating.

Table 46. Recommended surface preparation for specified coatings.

Coating Type	Surface Preparation		
Alkyds	Commercial Blast[1]	SSPC-SP-6	NACE #3
Acrylic Enamel	Commercial Blast[1]	SSPC-SP-6	NACE #3
Acrylic Latex	Commercial Blast[1]	SSPC-SP-6	NACE #3
Chlorinated Rubber	Commercial Blast[2]	SSPC-SP-6	NACE #3
Coal-Tar Coatings	Commercial Blast[2]	SSPC-SP-6	NACE #3
Epoxies	Near White Blast[3]	SSPC-SP-10	NACE #2
Epoxy-Phenolics	Commercial Blast[1]	SSPC-SP-6	NACE #3
Phenolics	Near-White Blast[3]	SSPC-SP-10	NACE #2
Modified Phenolics	Commercial Blast[1]	SSPC-SP-6	NACE #3
Polyurethane	Commercial Blast[2]	SSPC-SP-6	NACE #3
Vinyls	Commercial Blast[2]	SSPC-SP-6	NACE #3
Zinc (inorganic)	White Metal Blast[4]	SSPC-SP-5	NACE #1
Zinc (organic)	Near-White Blast[3]	SSPC-SP-10	NACE #2

[1]Where a compromise or alternate is necessary Brush Off Blast (SSPC-SP-7) may be used.
[2]Use Near-White Blast (SSPC-SP-10) for immersion or other severe exposure.
[3]Use Commercial Blast (SSPC-SP-6) where exposure is not severe.
[4]Near-White Blast (SSPC-SP-10) may be used where exposure is not severe.

(3) Abrasives. In addition to the degree of surface cleanliness recommended in Table 45, it is necessary that close attention be given to the surface roughness (profile), as illustrated in Figure 95. If the pattern of peaks and valleys is too shallow, proper adhesion may not be obtained and if the pattern is too deep and irregular, pinpoint rusting can occur because the prime or first coat may not cover the peaks. Generally, it is believed that the anchor pattern should not exceed one-half of the dry film thickness of the first coating applied (the prime coat). This, however, is not always true for high build primers or mastics.

For surface preparation, the manufacturers' recommendations with respect to the degree of cleanliness and the depth of the anchor pattern should always be carefully followed.

Table 47 indicates the average height of profile produced by different abrasives. The profiles will vary to some extent, with the angle and velocity of the abrasive particles and different hardnesses of the steel surfaces being blasted. Under most conditions, it is possible to protect the surface with a coating system which provides a total dry film thickness of 0.13 to 0.25 millimeter (5 to 10 mils).

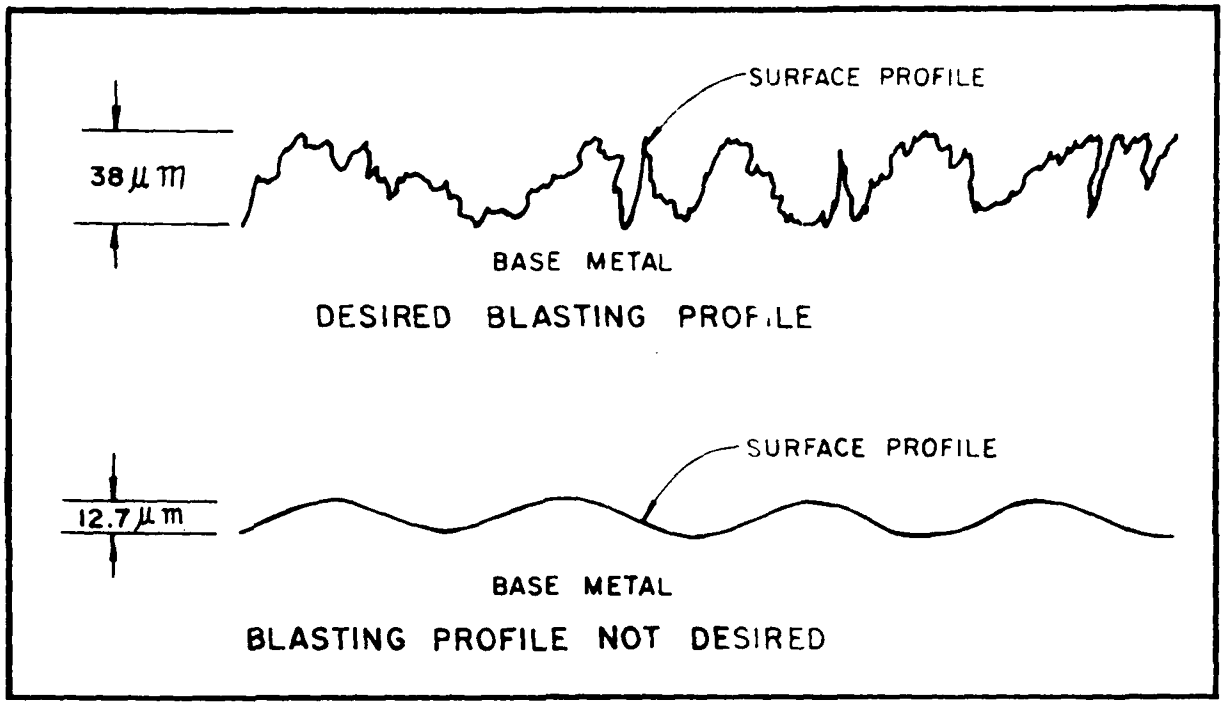


Figure 95. Surface blasting profiles.

Table 47. Types, sizes and resulting profile of abrasives used in airblast equipment.

Abrasive	Maximum particle size passing through ASTM mesh	Average height of profile (mils)	(µm)
Sand, very fine	80	1.5	40
Sand, fine	30	2.0	50
Sand, medium	18	2.5	65
Sand, large	12	2.8	70
Steel grit #G-80	40	1.3 to 3.0	30 to 75
Iron grit 3G-50	25	3.3	85
Iron grit #G-40	18	3.6	90
Iron grit #G-25	16	4.0	100
Iron Grit #G-16	12	8.0	200
Steel shot #S-170	20	1.8 to 2.8	45 to 70
Iron shot #S-230	18	3.0	75
Iron shot #S-330	16	3.3	85
Iron shot #S-390	14	3.6	90

In normal sandblasting, the anchor pattern should run about 38 to 50 micrometers (1.5 to 2.0 mils) deep. Most manufacturers recommend a 16-to 30-(16/30) mesh silica sandblasted at the surface at 690 kilopascals (100 pounds per square inch) to produce this profile pattern. An 8/30 mesh sand may be needed to remove tightly adhering rust and paint. Seldom are anchor patterns of more than 75- to 100-micrometer (3 to 4 mils) depths recommended, even for high build mastic coatings of up to 5-millimeter dry film. This profile can usually be achieved by use of 8/30 mesh silica sand, blasted at the surface with a nozzle pressure of 690 kilopascals.

Zinc-rich coatings on the other hand require a blast by 30/60 mesh sand to produce a required profile of 25 to 40 micrometers (1 to 1.5 mils).

Other abrasives include garnet, flint, steel grit, steel shot, and aluminium oxide. Costly abrasives, such as steel shot and steel grit, are primarily used where they can be recovered and reused such as in cabinets and blast rooms. Special equipment such as surface profile comparator furnished by Zorelco and NACE TM-01-70 visual standard should be used to verify the surface roughness (anchor pattern) produced by various abrasives.

(4) Sandblasting.

(a) Requirements. No coating system can perform better than the surface to which it is applied. It must be able to reach and adhere to that surface in order to perform its function. In general, as previously stated, sandblasting steel for use in harbor facilities provides the best and often the only suitable foundation for the majority of materials which should be used in these environments. In addition to removing surface contaminants, sandblasting produces surface roughness known as anchor pattern which enhance coating adhesion. Sandblasting, therefore, is one of the most important steps to consider in any protective coating program.

(b) Compressed Air Supply. This is perhaps the most critical part of a sandblasting operation. Speed of work and results will be accomplished only in direct proportion to the volume and pressure of air passing through the nozzle. To achieve good economics and a good profile, sandblasting steel requires a high nozzle pressure of 620 to 690 kilopascals (90 to 100 pounds per square inch) and high volumes of air at 2.5 to 10 cubic meters per minute (80 to 350 cubic feet per minute). The larger the nozzle, the faster the work will be completed, assuming proper air pressure.

It is generally recommended that an additional 35 kilopascals (5 pounds per square inch) compressor pressure should be used for each additional 15-meter (50 foot) length of blast hose. When only low nozzle pressure is

available (such as with long hose), the blasting rate will be slow, making removal of mild scale, old rust, paint or heavy marine growth expensive or incomplete.

The efficiency of blasting at 655 kilopascals (95 pounds per square inch) is only 50 percent of that of 690 kilopascals (100 pounds per square inch). Lower pressures also often result in other problems, such as the need to compensate by using larger sized abrasives with their attendant deep anchor pattern.

(c) Air Supply and Couplings. These should be related to the size of the job but generally should be as large as possible in order to supply a constant high volume of air at proper blasting pressure. For large jobs large air lines and couplings should be used in order to minimize friction loss through the hose. Universal type couplings are recommended for use on air lines.

(d) The Sandblasting Machine or Pot. For successful low cost blasting, the sand pot must also be given careful consideration. There are several types available. All furnish a regulated amount of abrasive to a high-pressure airstream for the blasting function. However, pots with only one chamber are normally used for intermittent blasting, while a two-chamber pot is better adapted to continuous work. Many sizes as well as designs are available. Proper size is determined by the abrasive capacity desired. All sand pots used for abrasive blasting should be equipped with a separator to remove any moisture or oil contamination. The separator trays must be emptied and maintained on a regular basis.

(e) Moisture Traps and Oil Separation. A moisture trap prevents condensation from forming on the lines and flowing onto the work surface. It should be placed as close as possible to the sandblast pot. An oil separator should be placed on air lines between compressor and blast machine to prevent oil contamination of the blasted surface. Although these items are frequently disregarded, they are important in obtaining a good coating job. If moisture or oil contamination are allowed to remain in the compressed air, they will contaminate the surface and degrade the quality of the coating job.

Water contamination will oxidize and corrode the surface, resulting in reduced quality of the final coating system. Oil contamination will reduce the adhesion properties of the final coating system and can cause delamination.

(f) Size of Hose With External Couplings. Sandblast hoses are often too small. The inside diameter of the hose should be three to four times the orifice size of the nozzle. Avoid any coupling or pipe-fitting connection that fits internally into hose. This can reduce the inside diameter enough to reduce the air-carrying capacity by more than 50 percent. Use only externally fitted quick couplings.

(g) Size and Type of Nozzle to be Used. Abrasive consumption and the volume of air used are directly related to the size nozzle being used. Most commonly used nozzle sizes are 6.4 , 8 , and 19-millimeter (1/4, 5/16, and 3/4 inch) inside diameter. The larger the nozzle the larger the

area cleaned in a given time. Example: at 690 kilopascals a 9.5-millimeter (3/8 inch) nozzle will clean 2.25 times the rate of a 6.4 millimeter (1/4 inch) nozzle.

(h) Sand and Abrasive Consumption Rates. Sand is the most widely used abrasive and for this reason, will be used as the basis for consumption rates presented. Other abrasives, infrequently used, include aluminum oxide, walnut shells, steel shot and steel grit. Rates for other materials are related in general to sand consumption rates. Specific consumption rates for each material will depend on the specific density of the abrasive and its velocity.

Upon impingement on a surface, the energy released by an abrasive particle will be directly related to its cleaning rate. That is, the more energy released, the faster the cleaning rate. The energy of a particle in motion is determined by its mass and its velocity according to the equation $E = 1/2\ MV^2$, where E is the energy of a moving abrasive particle (energy is released when particle strikes the surface), M the mass of abrasive particle, and V the velocity. Thus, the cleaning rate increases as the mass and velocity increase.

Sand consumption rates and airflow consumption are presented in Table 48. The increased sand and air consumption results in a greater area being cleaned per hour. The actual production per hour is affected by the condition of the surface to be prepared for coating and the cleani[illegible] or surface preparation to be achieved, as shown in Table 49.

Table 48. Sand and airflow consumption.

Nozzle Diameter (mm)	Nozzle Pressure (kPa)						
	344.7	413.7	482.6	551.6	620.5	689.5	
3.2	.32 298	.37 342.5	.43 391.4	.48 449.2	.52 498.2	.57 547.1	Air (m^3/min) Sand (N/hr)
4.8	.74 667.2	.85 760.6	.93 871.8	1.08 960.8	1.16 1058.6	1.27 1174.3	Air Sand
6.3	1.33 1192	1.53 1387.8	1.73 1574.6	1.92 1814.8	2.09 1992.8	2.29 2197.3	Air Sand
7.9	2.18 2081.7	2.52 2375.2	2.86 2686.6	3.2 2989	3.57 3291.5	3.88 3611.8	Air Sand
9.5	3.06 2971.3	3.57 3398.3	4.05 3843.1	4.56 4270.1	4.9 4679.3	5.55 5124.1	Air Sand
11.1	4.16 3985.4	4.81 4590.3	5.49 5230.8	6.14 5835.8	6.79 6440.[illegible]	7.19 7045.6	Air Sand
12.7	5.52 5159.7	6.34 5912.5	7.13 6725.4	7.92 7472.6	[illegible] [illegible]	9.57 9002.8	Air Sand

(i) Sandblasting Techniques. Sandblasting operations should be carried out to follow particular procedures:

(1) Strict adherence to the manufacturer's operating instructions;

(2) careful following of all safety regulations and proper use of safety equipment;

(3) holding nozzle at proper altitude and angle for surface area being cleaned;

(4) removing any and all dust after blasting with vacuum or brush (the latter is very important to avoid coating adhesion problems); and

(5) particular attention to inside corners, pits, edges bolt threads, nuts and bolts, welds and overblasting; the latter means blasting near an area already coated and allowing the abrasive to hit the coated areas.

Table 49. Approximate sand usage and labor rates on sandblasting.

Condition of Surface to be Prepared	Surface Preparation to be Achieved							
	SSPC-SP-5 White		SSPC-SP-10 Near White		SSPC-SP-6 Commercial		SSPC-SP-7 Brush	
	S[1] (N)	L[2] (m^2)	S[1] (N)	L[2] (m^2)	S[1] (N)	L[2] (m^2)	S[1] (N)	L[2] (m^2)
Loose Mill Fine Powder Rusting	478	11.6	383	14.4	192	23.2	96	37.2
Tight Mill Scale and Little Rust	575	8.4	479	10.7	287	18.6	96	33.4
Existing Coating Which is Failing	958	6.5	766	8.4	383	13	72	29.7
Badly Pitted Steel	1197	4.6	958	6.5	575	9.3	72	27.9

[1] S denotes abrasive usage per square meter.

[2] L denotes labor production per hour.

Note: These figures are approximate and reflect work on large areas such as tanks or large "I" beams.

e. Coating Application.

(1) Introduction. The goal of coating application is to place a continuous, uniform coating of sufficient thickness that is securely bonded to the substrate. Coating application is initiated after surface preparation has been satisfactorily completed and inspected. The prime coat should be applied prompt.y after the surface is cleaned, as cleaned steel is easily rusted if it is not protected. Coating application must be made under good dry conditions. If temperature is low enough that drops can occur and cause condensation on the surface, coating application should not be undertaken.

Coating specifications usually designate that coating work not be undertaken unless the temperature is 3^{o} to 6^{o} Celsius above the dewpoint (the temperature at which condensation will occur at a given pressure and relative humidity). Coating application can be by brush, roller, spray, or dip.

(2) Brush. Application of coatings by brush is one of the oldest and most widely used procedures for coating application. Maintenance and repair work are frequently done by brush, particularly if the size of the job is small. Most alkyds and a limited number of other products with good wetting properties can be applied by brush. Some manufacturers recommend that the prime coat be brushed on to ensure that it has been worked well into the surface. This is a desirable procedure when the surface is rough or when the surface preparation is poor.

When brushing is called for, the primer is often thinned to improve flow-out on the substrate. If the surface is rough or pitted, brushing will help work the coating into the roughened surface. The ability of a primer to protect will be directly related to surface wetting. If areas of the surface are not wetted by the primer they will be subject to corrosion. When conditions dictate that a brush be used for touchup work, tacky materials should be applied by liberally filling the brush and quickly applying it to the surface with a minimum amount of brush out. One advantage to application by brush is that there is only 4 to 8 percent loss of material (as opposed to 20 to 40 percent by conventional spray.)

Brushes must be of best quality and appropriate style. Brushing should be done in such a manner that a smooth coat as nearly uniform as possible be formed. It must be worked well into all crevices and corners and be applied without runs or sags, and with a minimum of brush marks.

In short, brushing is used by professionals only when it is specified or recommended by the coating manufacturer, where surface preparation is relatively poor, and for touchup work where spraying is unsuitable because of plant or area regulations.

(3) Roller. This method of application, like brushing, is fine for some materials and poor for others. Roller coating is generally used for applying alkyds and water-based (latex) materials over large areas such as tanks and buildings. These tools are also called into play because of regulations against any spray fog. Fast dry lacquer-type products will dry on the roller and do not dissolve in dipping. Others also show poor flow-

out properties. Pickup of the undercoat is another problem which must be considered as a possibility with rolling.

Rolling is a faster method of application than brushing. Roller coating has the same relatively low material loss as contrasted with conventional spray. Particular care must be exercised when using a roller on rough spots, pits, rivet heads, edges, corners, welds and the like, to make certain they are properly covered. Roller coating however, like brush application, is especially useful where spraying cannot be used because of spray fog and possible flammability of solvent.

(4) Spray.

(a) Introduction. Protective coatings, including many relatively small jobs, are applied by either conventional or airless spray in almost all industrial work. Wastage of materials is higher because of the fine atomization of the coating. The advantages of spray application are its coverage speed and application uniformity. Newer spray methods include hot airless spraying, electrostatic spraying, and combine speed with low material loss. Hot airless, as the name implies, is simply a heated airless spray application. Electrostatic techniques involve putting a charge on the spray particulate and the opposite charge on the work piece being coated so that the coating is electrostatically attracted to the part. Spray coating has the obvious advantage too of relatively easy application in corners, cracks and crevices. The newer spray methods also practically eliminate overspray and spray fog.

(b) Conventional Air Spraying. The spray gun in simple terms is a tool using compressed air to atomize products and apply them to a substrate. Air and coating enter the gun through separate passages which brings the two together and mixes them at the air cap. Most spray guns have two adjustments. One regulates the amount of fluid which passes through the gun when the trigger is pulled. The other controls the amount of air passing through the gun. This controls the fan spray width. The internal mix gun mixes air and material inside the cap before expelling them. This gun is generally used where only low air pressure is available or where slow-drying products which do not contain abrasive particles are to be applied.

The external mix gun mixes and atomized material and air outside the air cap. This type is more commonly preferred. Other types include automatic, extension and special spray guns.

(c) Airless Spray. This method of applying coatings uses no air for atomization. Hydraulic pressure is used to atomize the fluid by pumping it at high pressures through an accurately designed small orifice in the spray nozzle which controls the fluid flow and spray pattern. The air-operated hydraulic fluid pump multiplies many times the air input pressure to deliver material at desired spraying pressures. Various size caps are required since coatings do not atomize the same due to variations in coating pigment grind, viscosity and other formulation features.

Not all coating materials can be applied by airless spray. Many heavy, pigmented, and fiber-filled abrasive materials cause some problems

and are difficult to spray. However, there are considerable advantages to the use of airless spray. One major factor is the almost complete absence of overspray. There is less tendency for material to bounce, thereby, providing less air contamination and coating porosity. It is ideal for large flat areas such as tanks and walls, where speed is an asset and good coverage is required.

The maneuverability and convenience of this equipment, especially when working in confined areas, is another plus. Where heavy coating thickness is needed, airless is the desired tool. Table 50 shows comparable material losses for various application methods.

Table 50. Estimated loss of coating materials during application.

Method	Loss (pct)
Conventional Air	20 to 40
Hot air spray	15 to 30
Airless spray	5 to 20
Electrostatic spray	5 to 15
Brush and roller	4 to 8

(5) Dip. Coating work can be accomplished by dipping. Most galvanizing is by dipping. Parts which have a high surface area to weight ratio and which are relatively small can be dip coated in coating baths. This would include items such as gratings, ladders, and fence. The quality of a dip coating depends on the surface preparation and the application. The surface of the part being coated must be clean, free of contamination, and have the right profile for the coating being applied. Most coating systems can be applied by dip. These include alkyds, coating systems which cure by evaporation (e.g., vinyls and acrylics) and coating systems which cure by reaction (e.g., epoxies and urethanes).

As stated above, the quality of dip coatings depends not only on the surface preparation, but also on the application. The dip bath must be properly and continuously stirred and agitated, so that the pigments and other coating components are uniformly dispersed in the bath. The temperature of the part and of the bath should be controlled to lie within the range recommended by the coating manufacturer. Coatings which cure by reaction have a limited application life. This life is dependent upon the temperature. The higher the temperature, the shorter the life. Care must be exercised not to apply coatings which have exceeded their effective application life.

Care must also be exercised in the application of coatings which cure by evaporation. Solvent must be added from time to time to make up for the solvent lost to the atmosphere by evaporation. Dipping work should be stopped during the application of solvents, and it should not be commenced again until the added solvent is thoroughly and uniformly dispersed. Parts which are dipped are often "turned" while curing, in order to avoid drips and runoff "strings" from the bottom edges. Heat and air movement may be used to increase the cure rate (to shorten the cure time).

(6) Coating Coverage. The volume of a 3.785 liter (one gallon) container of paint is 0.003 8 [illegible] cubic meter ([illegible] cubic inches), according to the U.S. Bureau of Standards. If the paint is 50 percent solvent which volatilizes as the coating cures, the effective remaining paint for surface coverage (paint film) is [illegible] cubic meter (115.5 cubic inches). Some paint products [illegible] than 50 percent solvent, others contain less, and there [illegible] contain no solvent; i.e., they are essentially 100 percent [illegible] cubic meter of nonvolatile material is spread [illegible] film 25.4 micrometers (1 mil) thick, it will cover [illegible] square meters ([illegible] square feet).

If the coating [illegible] percent volatile solvent (by volume), its surface-covering [illegible] reduced 50 percent. At a 25.4-micrometer dry film coating thickness, it [illegible] cover 75 square meters (802 square feet). The coating as applied will be "wet," containing 50 percent solvent (by volume). It will be [illegible] meters (2 mils) thick. As the solvent evaporates its thickness will decrease. Where all the solvent has volatilized (vaporized) the dry film thickness will be 25.4 micrometers. As mentioned earlier, coating thickness will vary from 38 to 76 micrometers for alkyds and up to 250 to 760 micrometers for heavy coal-tar coatings or mastics.

f. Inspection. Coating inspection work starts with the surface preparation. Details relating the degree of surface cleanliness to the surface preparation specified are found in the Steel Structures Painting and will not be discussed here. Coating application must be in strict accordance with the coating manufacturers' recommendations. Inspection of coating application, including touchup, repair, and maintenance work, will be centered around compliance with these recommendations.

Inspection will include items such as making sure that coatings with dense pigments (such as zinc-rich coatings and red lead primers) are continuously stirred during application, measuring and recording both the air and the surface temperature and the humidity, determining the shelf life of the coating, and using it within its shelf life, and becoming thoroughly familiar with the coating products being used and the manufacturers application procedures.

g. Coating Repair and Maintenance. During construction there will be damage to the coating system. Also, after erection, welding areas (weld lanes) will require surface preparation and coating. This section will consider touchup and repair of these areas before going into maintenance coating work. Priming is frequently done before erection. After erection the weld lanes are cleaned and primed and the coated areas damaged during erection are repaired.

Inorganic zinc is also frequently used as a preconstruction primer because of its toughness (resistance to damage) and its excellent corrosion resistance. Organic zinc-rich primers (such as epoxy zinc riches) are often used for weld lanes and repair work after erection. The organic zinc-rich coatings have better adhesion qualities and are "more tolerant" of imperfect surface preparation than the inorganic zinc coatings. Other primers utilized for weld lane touchup work include primers from all the generic coating classes, including alkyds, vinyls, epoxies, universal (a primer which can be topcoated with any topcoat without lifting, usually containing a phenolic resin).

Final topcoating after erection is considered good practice. Topcoating before erection is infrequent because of the damage problem during erection. Damaged coatings should be removed. Abrasive grinding or wire brush procedures may be used for removal. The edges of the adjacent nondamaged coated areas should be feathered and slightly roughened (for good adherence of the repair coating). The repair coating system should be applied and should overlap the previous coating about an inch or two.

Touchup and repair topcoats are usually semigloss. Most industrial coating systems utilize a semigloss topcoat rather than a high gloss topcoat. Semigloss colors are much easier to match (in texture and color). High gloss products tend to show up any slight variations of color or texture.

Maintenance of a coating system is essential for long life and minimum cost. In general, all critical areas including splash zones and the like should be inspected at least once a year. Protective coatings, regardless of type and service, will eventually wear or erode away. They require periodic touchup and restoration. The effective service life of a coating system will vary widely with the service condition, as well as coating type, surface preparation and application. For good coating life, no fixed maintenance program can be developed, unless accurate periodic inspection records are kept. The most effective time for maintenance work will require careful analysis of the periodic examination records.

The expense of corrective maintenance work can be greatly reduced by proper timing, as well as the choice of the proper repair materials. A good maintenance program will initiate repair work before coating failure. It is simple and inexpensive to apply a fresh topcoat. It is costly and time consuming to remove a failed coating, clean the surface and reapply a coating system (primer and topcoat). In choosing a repair topcoat it is important to select a product which will adhere to the old coating and one which is compatible. It is recommended that product suppliers be consulted in such choices. When the coating failure is greater than 10 percent or there is widespread delamination, cracking or incipient surface rusting, it is best to remove the old coating completely and recoat. The best maintenance program is a good inspection program coupled with the application of a fresh topcoat before excessive failure initiates. A good weathering topcoat, such as an acrylic, can add many years of life to a coating system at minimum cost.

h. Specifications. A satisfactory coating system and protective coating program begins with the specifications. Yet, many coating specifications are vague and wordy. All too frequently, the importance of developing a structure is given so much time and preoccupation that the architect-engineer underemphasizes the necessity for clear-cut coating specifications to protect the structure.

Writing appropriate coating specifications will do more than almost any other one phase of coating work to achieve long life economical protection in any harbor facility. These specifications play a conspicious role in terms of both initial cost and a cost per square meter per year of service life.

Many specifications, primarily because of efforts to streamline this aspect of the job or to place them in the category of "routine work," open

loopholes for contractors resulting in poorer jobs due to specification interpretation. Thus the coating specifications should be as brief as possible without forfeiting any of the primary objectives. They should be written in such a manner that the contractor can present his bid wisely, efficiently and competitively, and such that coatings will be applied in strict accordance with all requirements.

A good coating specification should contain the following:

(1) A scope of work (a general description of the job, its location, and work to be done);

(2) a detailed listing of the products, preferably by brand name (including those that may have been evaluated) or military (MIL) specifications where required;

(3) a full description of the methods and equipment required to do all phases of the work (surface preparation, application and inspection).

(4) identification of the material supplier's responsibility to supply quality coatings that meet specific performance requirements or are manufactured to meet specific formulation requirements;

(5) safety requirements to ensure proper procedures in sandblasting and application work;

(6) the quality of workmanship requirements spelled out to include cleanup work, work logs expected, inspection acceptance, and prevention of contamination of nearby structures;

(7) a "coating schedule" that shows exactly what is to be applied, where, when, and how; and

(8) inspection requirements to show what inspection measurements and reports are required.

i. Safety. The combustible and toxic nature of protective coatings must be considered during application and during the cure period. Special precautions are required when coatings are applied in confined or enclosed areas. Containers should always be opened in a well-ventilated area and kept away from open flames or sparks. Proper ventilation must be provided to prevent possible buildup of explosive or toxic materials. Inhalation of toxic fumes and dusts whether inside or outside, must be avoided. Suitably designed air masks should be worn while spraying in these locations. The manufacturers' safety requirements must be studied and followed.

3. Cathodic Protection.

a. Types and Application Methods of Cathodic Protection.

(1) Sacrificial Anodes. The simplest way to make the subsurface structure "all cathode" is to install galvanic or "sacrificial" anodes in the electrolyte and electrically connect them to the substructure. The

anodes may be made of magnesium alloy (usually used in soil), aluminum alloy (usually used in seawater), or zinc alloy (used in either soil or water). Alloys are used because in the cases of the three metals mentioned, certain alloys of each result in greater efficiency (i.e., one or more of higher output current, higher output voltage, or longer life) than is possible when using the pure unalloyed metal.

Aluminum or zinc anodes are used in seawater or freshwater. Magnesium may also be used, but its cost is higher and its life per newton is shorter. Zinc and magnesium anodes for use in soil are installed with a chemical backfill completely surrounding the anode. The backfill material should be uniform to provide current efficiency. (With a nonuniform backfill, the anode will supply increased currents where the backfill has low resistivity, thus wasting the anode more rapidly in these areas.) A uniform backfill will also aid in keeping the anode continuously moist and will prevent anode contact with adverse materials that may be in the soil. Low backfill resistivity has the same effect as increasing anode size, thereby decreasing effective anode resistance to earth.

Magnesium anodes in prepackaged backfill are available in many sizes. The anode with surrounding backfill is contained in a cloth sack or porous tube. Backfill commonly supplied with prepackaged magnesium anodes is 75 percent gypsum, 20 percent bentonite alloy, and 5 percent sodium sulfate, but other mixtures usually are available on request. Magnesium anodes are normally furnished with a 3-meter (10 foot) No. 10 or No. 12 AWG copper lead wire with Type TW insulation.

Zinc anodes are normally not sold in prepackaged backfill or with leads attached due to difficulty in handling the much heavier anodes. If not provided with prepackaged backfill, galvanic anodes in soil should be installed completely surrounded by well-tamped chemical backfill material to ensure best utilization of anode material. Chemical backfill material for either magnesium or zinc anodes is shown in Table 51. No backfill of any kind is used with anodes in water.

Zinc and aluminum anodes, without backfill, are particularly useful in seawater where the low resistivity electrolyte permits good current output in spite of the relatively low anode driving potential. Magnesium is not suitable for seawater use because of the low efficiency caused by the tendency of magnesium to "self-corrode" in the low resistivity electrolyte.

Whether or not a galvanic anode system will work depends on the electrical circuit resistance and on the current required for protection. The circuit resistance is determined almost entirely by the resistivity of the electrolyte environment. Galvanic anodes work best in low resistivity electrolytes such as seawater with a resistivity of 16 to 20 ohm-centimeters. Good performance usually is obtained through 1 000 ohm-centimeters. They have been made to work in resistivities as high as 2 000 ohm-centimeters when conditions permit use of the limited output current. The output current is necessarily limited by the relatively low driving potentials of all types of galvanic anodes. Table 52 shows approximate data for some common anode materials.

Current required for protection is based on current density requirements, usually stated in milliamperes per unit of area. Bare steel in

Table 51. Chemical backfill for galvanic anodes in soil.

Back-fill Mix	Gypsum ($CaSO_4$) Hydrated (pct)	Gypsum ($CaSO_4$) Molding Plaster (plaster of paris) (pct)	Bentonite Clay (pct)	Sodium Sulfate (pct)	Approx. Resistivity, Ohm-cm
----[1]	25	-	75	-	250
----[2]	50	-	50	-	250
----[3]	-	50	50	-	250
----[4]	75	-	20	5	50

[1]Useful in low soil moisture areas. Utilizes moisture-holding characteristic of bentonite clay.
[2]Usually used with zinc anodes.
[3]Useful with zinc or magnesium in wet or marshy soils. Prevents rapid migration of backfill from anode surface.
[4]Low resistivity; useful in high soil resistivity to reduce anode resistance to earth. Type usually furnished with prepackaged magnesium anodes.

Table 52. Approximate data for common galvanic annode alloys.

	Zinc alloy in soil[1] or seawater (Mil Spec. A-18001)	Magnesium Alloys in Soil[1] Standard (H-1 Alloy)	Magnesium Alloys in Soil[1] High potential (Galvalum Alloy)	Aluminum Alloy in seawater (Galvalum Alloy)
Specific Gravity	7.14	1.94	1.94	2.77
Kilonewtons per Cubic Meter	69.1	19.0	19.0	-
Theoretical Ampere Hours per Newton	84	225	225	302
Current Efficiency (pct)	95[2]	50[3]	50[3]	95[2]
Actual Ampere Hours per Newton	79[2]	112[3]	112[3]	288[2]
Actual Newtons per Ampere-Year	111	76[3]	76[3]	31
Solution Potential (volts)	-1.1[4]	-1.55[4]	-1.80[4]	-1.1[5]
Driving Potential, (volts)	-0.25[5]	-0.60[7]	-0.85[7]	-0.25[6]

[1]Anodes in suitable chemical backfill.
[2]Current efficiency of zinc and aluminum reasonably constant over wide range of output.
[3]Current efficiency of magnesium varies with current density. Figures given are for approximately 300 milliamperes per square meter of anode surface.
[4]To $CuSO_4$ reference cell in neutral soil.
[5]To $CuSO_4$ reference cell in seawater.
[6]Solution potential, the equilibrium potential of a metal exposed in a given solution, minus the polarized potential, the potential of a metal after the flow of sufficient current to come to equilibrium (-0.85 volts to $CuSO_4$ reference electrode).
[7]Solution potential minus polarized potential of protected structure minus approximately 0.1 volt for anode polarization in service.

average soil or quiescent seawater usually is considered to be about 10 milliamperes per square meter (1 milliampere per square foot). Any coating present, regardless of quality, can produce a drastic reduction in the current density requirement. Actual current required for a given substructure, of course, depends on the subsurface area exposed to the contacting soil or water. In the case of bare steel, 93 square meters (1 000 square feet) probably would require at least 1 ampere for protection. With wrap-coated steel pipe, approximate current density requirements may be estimated by reference to Table 53. These values are for guidance estimates only and may vary widely depending on specific conditions such as moving seawater.

Table 53. Current requirements for coated steel or wrapped pipe.

Age of Wrap or Coating	Approx. Current Density Required (mA/m^2)
1930 to 1950	1.1
1950 to 1960	0.54
1960 to 1970	0.32
1970 to Present	0.11

The actual current requirement requires that a calculation of the total area involved, in square feet, be made. Based on the current requirement, a decision can be made whether a galvanic system or impressed current system should be used.

(2) Impressed Current (Inert) Anodes. Driving potential of galvanic anodes may not be high enough to provide sufficient current for effective cathodic protection. This is particularly true when the subsurface structure to be protected is surrounded by an electrolyte of high resistivity such as is frequently encountered with steel in freshwater or soil. Also there are applications requiring higher current density than can be delivered economically by galvanic anodes. Examples of this would be protection of the external bottom surface of a large oil storage tank or either soil or water sides of a steel sheet-pile bulkhead. To be free from the limitations of galvanic anodes, an external power source may be used to provide "impressed" current for protection. Here, the required direct current driving voltage and current are limited only by the external source power availability. Various power sources may be used; the most common is commercial alternating current power connected to a low voltage transformer-rectifier combination (usually called simply a rectifier) to provide the required direct current with easily adjustable output voltage. This provides the means to counteract the flow of corrosion current to make the substructure "all cathode." A simplified diagram as applied to a pipeline is shown in Figure 96.

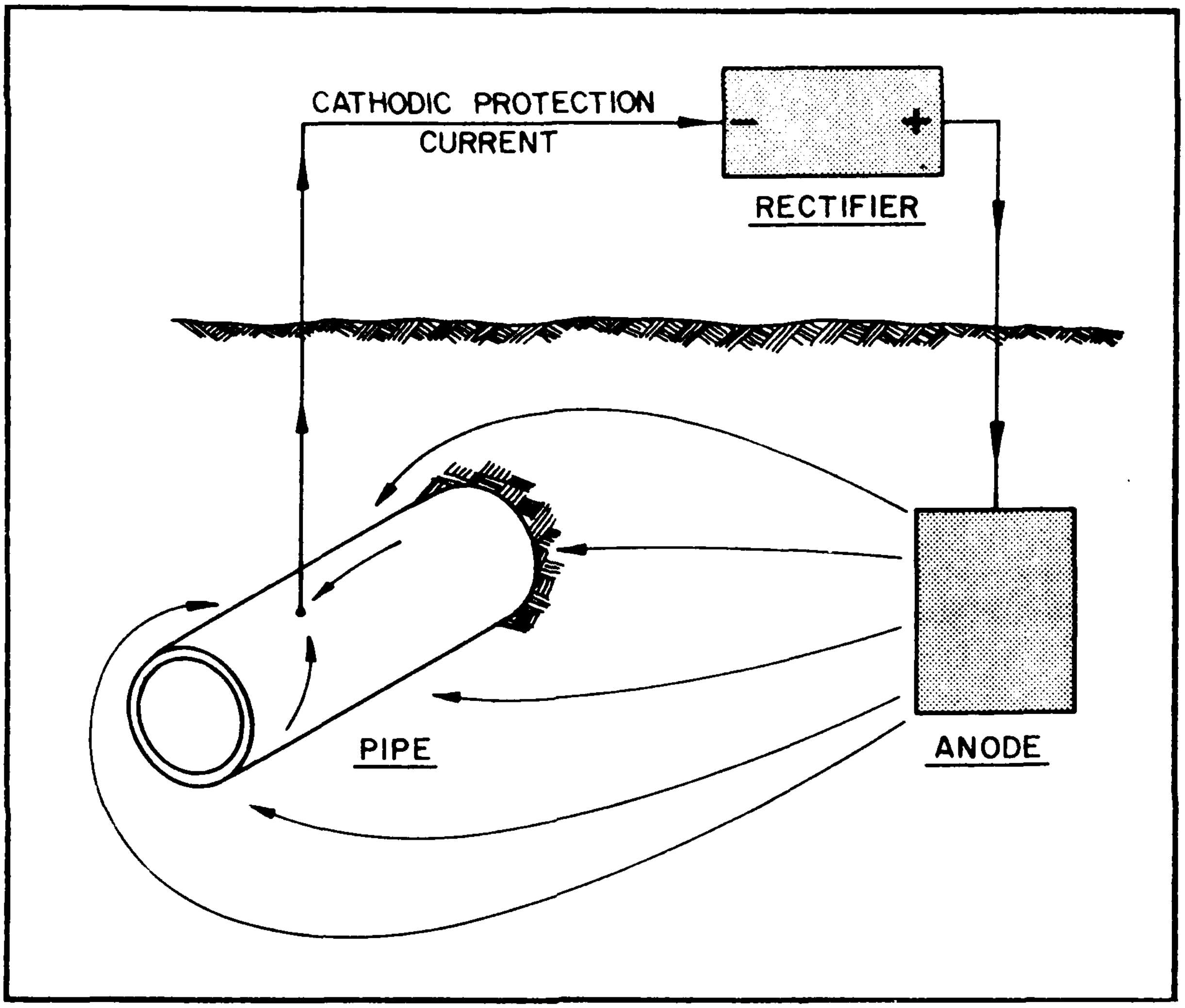


Figure 96. Diagram of simple impressed current cathodic protection.

Impressed current anodes differ from galvanic anodes in two important aspects: (1) the galvanic potential difference between anode and protected substructures is of no importance, and (2) the impressed current anode should be as inert as possible, i.e., have a very low consumption rate for long life. Consumption rates for various metals including those commonly used for impressed current anodes are shown in Table 40. Carbon or graphite, high silicon cast iron, magnetite, lead-silver, and platinum all have critical current densities above which rapid consumption may occur. The consumption rates listed for these materials assume operation below critical current densities.

As with galvanic anodes in soil, impressed current anodes in soil should be installed completely surrounded by backfill material. Impressed current anodes in water do not require backfill. Impressed current anodes in soil require a carbonaceous backfill, well-tamped to eliminate air pockets and to provide the best possible electrical contact, both with the anode and with the soil. Two functions are thereby served:

(a) The very low resistivity of the backfill material has the effect of increasing the anode size with a consequent reduction in resistance to surrounding soil; and

(b) most of the current flows to the backfill from the anode by direct electrical contact so that most of the electrolytic consumption is at the soil contact with the outer surface of the backfill column.

Resistivity of carbonaceous backfill should not exceed 50 ohm-centimeters. There are at least three materials in present use: coal coke breeze, calcined petroleum coke breeze, and manmade or natural graphite flakes or particles. All of these are basically carbon in low resistivity form. The term "breeze" is loosely defined as being a finely divided material. For backfill use, specific sizes are obtainable. Coke breeze should be procured by specification with particle size and resistivity being most important. Particle size should not exceed 9.5 millimeters (0.375 inch) and not more than 10 percent dust should be included. Petroleum coke breeze must be calcined to produce resistivity of 50 ohm-centimeters or less. Graphite flakes should not be used because of possible gas blockage problems (accumulation of gas around the cathode from the cathode reaction).

(3) Comparison of Anode Types. Cathodic protection for a given subsurface structure may be provided by either galvanic anodes or by impressed current anodes as long as respective limitations are recognized. Some of the more important characteristics of each method are listed in Table 54.

(4) Connections Between Anodes and Structures. In the case of galvanic anodes, the connecting wire from the anode is part of the cathode and bare areas resulting from cut or broken wire insulation or poorly insulated splices will be part of the protected structure and suffer no electrolytic damage. The opposite is true of impressed current anode systems. If any of the insulation is less than perfect, current discharge into the surrounding electrolyte (soil or water) will occur and the wire will corrode too quickly, producing failure of part or all of the system. This means that top-quality insulation must be used for all buried or

Table 54. Comparison of galvanic and impressed current protection systems.

Galvanic	Impressed Current
No external power required	External power source required
Relatively low installation and maintenance costs	Higher installation and maintenance costs
Frequently requires no additional right of way	Applied voltage and current may easily be varied
Adjusts current output as structure potential varies (especially zinc anodes)	Protects larger and more extensive structures
Severely limited current output	Suitable for high resistivity electrolytes
Useful primarily in low resistivity electrolytes	Monthly power bill
Interference with foreign structures usually non-existent.	Can cause interference problems with foreign structures.

immersed anode leads and header cables. Insulation should be 600-volt type and be suitable for direct burial service. High molecular weight, high density polyethylene has a good record for satisfactory use. Insulation quality of all subsurface electrical connections is equally important for the same reasons. Satisfactory electrical connection methods for copper wire include soft soldering, powder welding (such as Cadweld), silver soldering, phoscopper brazing, crimp-type couplings, and split-bolt couplings. The first four, if done properly, will provide metallurgical joining and will be permanently of low resistance. Mechanical methods such as the last two mentioned, again if done properly, will be satisfactory also. Joint insulation should be of such quality as to at least equal the electrical insulating qualities of the wire insualtion. Acceptable insulation methods include cast epoxy as well as various tapes. There are several manufacturers of cast joint insulation. Details of joining and insulating may be obtained from cathodic protection material supply house catalogs. In all cases, satisfactory performance life depends on the proficiency of the people doing the work. Careful inspection of all phases of impressed current anode installation is mandatory.

b. Criteria for Cathodic Protection. Earlier it was stated that if electric current is caused to flow from an external source through a common

[illegible] electrolyte, into a subsurface structure, corrosion current [illegible] corrosion will be stopped if the external current flow counter- [illegible] corrosion current at all parts of the substructure surface. In [illegible] case the substructure becomes all cathode and is protected against corrosion, i.e., if all areas on a corroding substructure are polarized (or [illegible]) to the same open circuit potential, corrosion will be impossible because there will be no potential difference between anode and cathode [illegible] no corrosion current can flow. In practice, the potential applied [illegible] surface, called polarization potential, must equal or exceed the open circuit potential of the most anodic area in order to stop all corrosion.

To determine when or if this condition exists, there must be some way to measure the potential existing between the protected substructure and [illegible] contacting electrolyte environment. Based on this concept, potentials should be measured directly across the interface between the substructure and its environment. This is relatively simple with marine substructures in seawater but is seldom feasible when working with substructures in soil such as pipelines or buried cylindrical storage tanks. Common practice with buried substructures is to measure the potential between the substructure and the soil at the surface directly above the substructure. The measured potential includes polarization potential plus a potential, usually called IR drop, caused by current flowing through a part of the resistance between the structure and the external anode installation.

(1) <u>Potential Measurement Apparatus</u>. As potential measurement is a useful approach to determining if corrosion is present or absent, potential measurement methods should be considered. The connection to the substructure usually is easily made by direct contact or by a suitable test wire connection. The actual measured potential will vary (sometimes drastically) with the method used to contact the environment. To get reproducible results this contact must be made through some stable and reliable reference. The method in common use for measurements of substructures in soil (and frequently in water) environments is by means of a copper-copper-sulfate half cell reference electrode contacting the electrolyte. It may be referred [illegible] as "copper sulfate electrode," "copper sulfate reference," "[illegible] sulfate half cell," "$CuSO_4$ electrode," or "CSE." The working parts of [illegible] copper sulfate electrode are shown in Figure 97, along with an equivalent circuit to illustrate the half-cell concept.

[illegible] silver-silver-chloride electrode is similar. Silver metal is in [illegible] with a 0.1 normal solution of silver chloride with a porous plug [illegible] the electrolyte.

[illegible] a few precautions to be observed when using any reference [illegible] Care must be taken to prevent contamination of the fluid in the [illegible] if its potential is to remain constant. Such contamination is [illegible] potential measurements in a fluid electrolyte such as [illegible] copper sulfate electrode, the observed potential will vary [illegible] temperature, showing a positive gradient of 0.9 millivolt per [illegible] volt per $^\circ$ Fahrenheit) up to about 50° Celsius (120° [illegible] hydrated copper sulfate begins to change structure. One [illegible] correction of all copper sulfate electrode potential [illegible] (77° Fahrenheit). Such precision usually is not [illegible] fieldwork. It is good practice, before measuring a

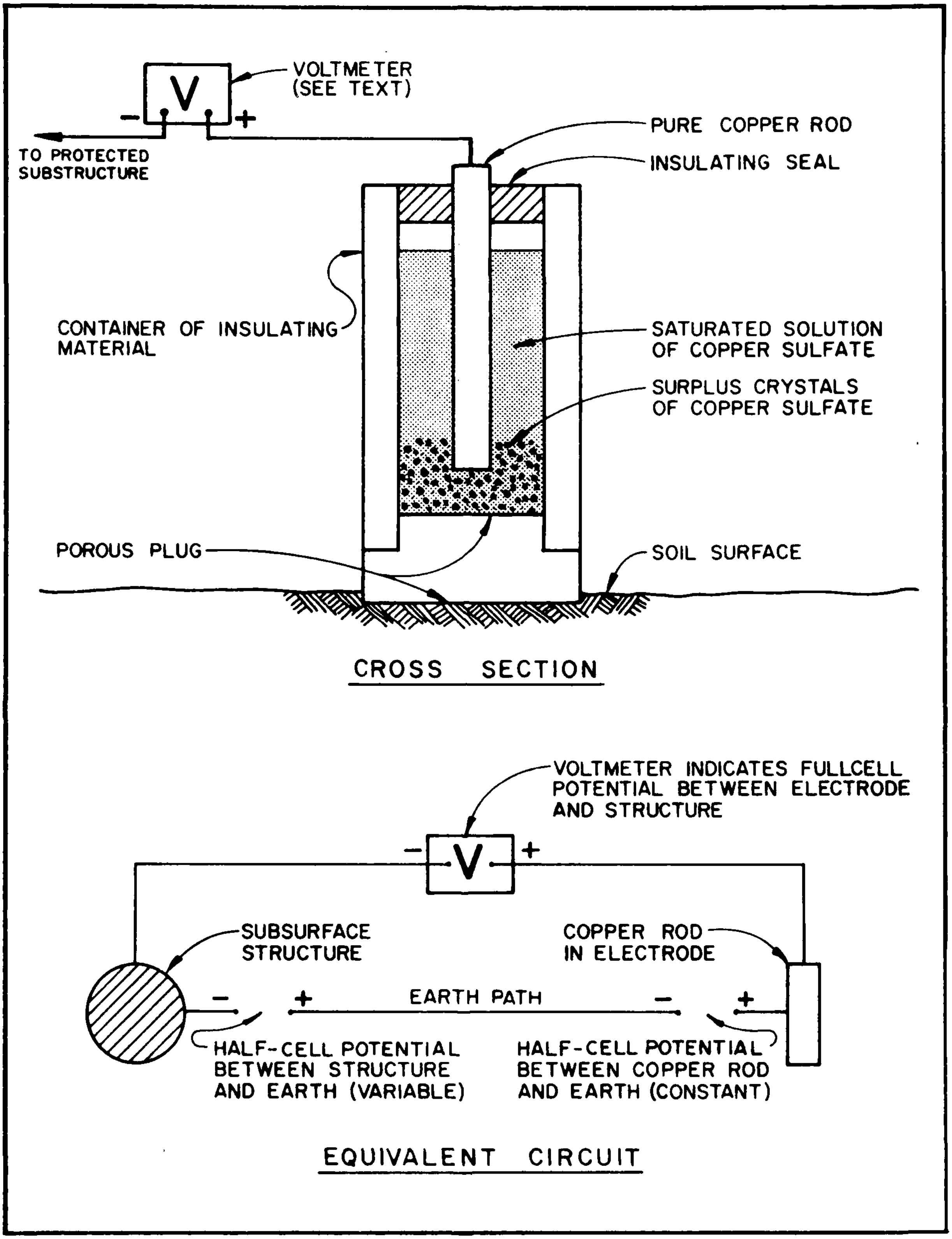


Figure 97. Copper sulfate electrode test circuit.

potential, however, to invert the electrode two or three times to equalize internal temperature.

All reference electrodes are subject to polarization to some degree when placed in an electrical circuit with current flowing. This means that any appreciable current drawn by the potential measuring circuit (voltmeter) would result in lower potential readings. In general, the accuracy of potential measurements will increase as the measuring circuit current approaches zero. The most accurate voltmeter suitable for field or laboratory use is the standard-cell potentiometer with a suspension-type galvanometer. When balanced for reading of potential, the reference cell current is zero. The most easily handled and easily operated instrument for general field use, ashore or afloat, is the electronic type, preferably with an input resistance (sensitivity) of 10 megaohms or more. This ensures a reference cell current of a fraction of a microampere. Conventional voltmeters of 1 000 or 5 000 ohms per volt are not suitable for these measurements.

When a suitable voltmeter is connected between the substructure and the reference electrode, the measured potential is a combination of the potential between the reference electrode and electrolyte (soil or water), and the potential between the substructure and electrolyte. The substructure-to-earth half-cell potential is the variable of interest. The reference half-cell potential is considered constant for practical engineering purposes. The copper sulfate electrode has been found to be practical for field use as its half-cell potential is reasonably constant over a wide range of conditions. The actual value of its half-cell potential is not important. The total cell potential, as measured, is the one used in engineering practice. This is the structure-to-electrolyte potential. Several discussions of the copper sulfate electrode covering its theory, history, and development are available in the literature (NACE, 1979).

It has been established that the most anodic areas to be expected on a freely corroding steel structure in moist soils and waters will show a potential of about -0.8 volt measured to a copper sulfate electrode contacting the electrolyte as close as possible to the anodic area. Allowing for some variation in potential of the most anodic areas, the value of -0.85 volt to a copper sulfate electrode contacting the electrolyte has been adopted as a practical indication of satisfactory protection. Wide and varied experience in many environments has indicated the accuracy of this criterion for practical field use.

While the copper sulfate electrode is by far the most common, other electrodes are in use. These include calomel (usually the saturated type), silver-silver chloride, and occasionally pure zinc. Other common metals are not sufficiently stable for reference electrode use. The calomel electrode, while very stable, is more adapted to laboratory work than field use because of its largely glass construction. The silver-silver chloride electrode also is quite stable and may be encountered frequently in marine operations. Pure zinc (Special High Grade, 99.99 percent pure) is occasionally used as a reference electrode but is subject to variations of as much as 50 millivolts, making it suitable only for approximate values. Table 55 shows the potential readings for these common reference electrodes compared to the reading for copper sulfate electrodes at 25^{o} Celsius (77^{o} Fahrenheit):

Table 55. Potential readings for various reference electrodes

Type of Reference Electrode	Structure-to-Electrode Reading Equivalent to -0.85 Volt to Copper Sulfate Electrodes (Volts)	To Correct Structure-to-Electrode Reading to Equivalent Reading to Copper Sulfate Electrodes (Volts).
Calomel (Saturated)	-0.778	Add -0.072
Silver-Silver Chloride (0.1 N Kel solution)	-0.840	Add -0.010
Pure Zinc (Special High Grade, 99.99 pct pure)	+ 0.25[1]	Add -1.10[1]

[1]Based on zinc open circuit potential of -1.10 volts to copper sulfate electrode.

(2) Measurement Techniques. NACE Standard RP-01-69 (1976 Revision), "Control of External Corrosion on Underground or Submerged Metallic Piping Systems," applies equally to any buried or immersed structure. The following information and criteria for cathodic protection are quoted from the above publication:

"6.2.3 The criteria in Section 6.3 have been developed through laboratory experiment or empirically determined by evaluating data obtained from successfully operated cathodic protection systems. It is not intended that the corrosion engineer be limited to these criteria if it can be demonstrated by other means that the control of corrosion has been achieved.

"6.2.4 Voltage measurements on pipelines are to be made with the reference electrode located on the surface as close as practicable to the pipeline. Such measurements on all other structures are to be made with the reference electrode positioned as close as feasible to the structure surface being investigated. The corrosion engineer shall consider voltage (IR) drops other than those across the structure-electrolyte boundary, the presence of dissimilar metals, and the influence of other structures for valid interpretation of his voltage measurements.

"6.2.5 No one criterion for evaluating the effectiveness of cathodic protection has proven to be satisfactory for all conditions. Often a combination of criteria is needed for a single structure.

"6.3.1.1 A negative (cathodic) voltage of at least 0.85 volt as measured between the structure and a saturated copper-copper sulfate reference electrode contacting the electrolyte. Determination of this voltage is to be made with the protective current applied.

"6.3.1.2 A minimum negative (cathodic) voltage shift of 300 millivolts, produced by the application of protective current. The voltage shift is measured between the structure surface and a stable reference electrode contacting the electrolyte. This criterion of voltage shift applies to structures not in contact with dissimilar metals.

"6.3.1.3 A minimum negative (cathodic) voltage shift of 100 millivolts measured between the structure surface and a stable reference electrode contacting the electrolyte. This polarization voltage shift is to be determined by interrupting the protective current and measuring the polarization decay. When the current is initially interrupted, an immediate voltage shift will occur. The voltage reading after the immediate shift, shall be used as the base reading from which to measure polarization decay."

Paragraphs 6.3.1.4 and 6.3.1.5 are not quoted as they apply only to specific situations not generally encountered.

The U.S. Department of Transportation has issued "Regulations for the Transmission of Natural and Other Gas by Pipeline, Part 192, Title 49," provisions of which are now in effect. Subpart I contains requirements for corrosion control. Criteria for protection are, in effect, identical with those in the NACE publication quoted above.

(a) Components of Potential Measurement. The voltage drop between two points in a medium is equal to the current flowing between the points, I, multiplied by the resistance of the medium R. For this reason, voltage or potential drops caused by current flowing through resistive electrolytes are called IR drops.

The NACE Standard RP-01-69, 1976 Revision, quoted above states, in paragraph 6.2.4, that IR drops are to be "considered." Unfortunately, there are still many workers in the field who ignore the IR drop contribution to potential measurements and continue to record structure-to-electrolyte potentials with no consideration of IR drop. In such cases the recorded potential will always be higher (more negative) than it actually is. If a reading of -0.85 volt was recorded, indicating protection according to the criterion given in Paragraph 6.3.1.1, the true potential, after deducting IR drop, may well be substantially below protective levels. The amount of error will depend primarily on electrolyte resistivity. Examples are shown in Table 56.

As can be seen in Table 56, the only time that IR drop can be ignored safely is when potentials are measured in seawater or similar electrolyte with a resistivity less than 50 ohm centimeters. In seawater the IR drop is

Table 56. Electrolyte IR drop in millivolts 1.5 meters from bare pipe.

Electrolyte Resistivity (Ohm-cm)	Pipe Diameter (in) (nominal)	IR Drop (mV)
50	1	0
50	5	1
50	15	2
50	30	3
5 000	1	33
5 000	5	110
5 000	15	225
5 000	30	331
50 000	1	328
50 000	5	1 100
50 000	15	2 250
50 000	30	3 309

Resistivity of seawater is generally about 20 ohm-cm
Current density = 10 milliamperes per square meter

usually negligible if the reference cell is within 1.5 meters (4.9 feet) of the substructure.

If the cathodic protection current ceases (turned off or otherwise interrupted), the IR drop ceases instantly. The potential of the protected structure (polarization potential) decays at a relatively slow rate compared to the IR drop, depending on several factors, and, of course, is free from IR drop. If this potential can be measured while the current is momentarily interrupted, it will be close enough to the true polarization potential for normal engineering purposes. This potential is usually known as the "OFF" or "INSTANT OFF" potential (as contrasted with the "ON" potential, read while protection current is flowing).

The relationship between the various potentials involved is shown in Figure 98. Prior to time of current OFF the only potential measurable is the ON potential which includes the IR drop. After that point it is that of the rapidly decaying polarization potential. The meter response curve shown is typical of a conventional high resistance voltmeter.

(b) Measurement of the Critical Component. In view of the preceding background on criteria, the criterion of -0.85 volt (-850 millivolts) with the current momentarily interrupted is recommended. With this criterion in use, the NACE criterion in paragraph 6.3.1.1 will be met. The criterion in paragraph 6.3.1.3 usually will be met also.

There are a few considerations. There should be provisions for reading the potential as soon as possible after interruption of the current, and, to minimize loss of polarization, for keeping the interruption period as short as possible. A simple way to do this is by means of the circuit shown in Figure 99. A single-pole double-throw microswitch is used to interrupt the cathodic protection current and at the same time connect the potentiometer voltmeter and reference electrode to the structure under protection. The voltmeter is adjusted to some expected value and the switch cycled as rapidly as possible. This will interrupt the current for about a tenth of a second. The indicating meter needle will kick up or down scale depending on the potentiometer setting. The voltmeter is adjusted in the direction of needle kick and the switch again cycled. This is continued until a narrow band, probably about 5 millivolts wide, is found where no needle movement is observed. The center of this band is very close to the true OFF potential. Care should be taken that the added resistance of the microswitch circuit does not appreciably reduce the rectifier output current. If necessary, the microswitch circuit may be used to drive a low resistance relay switching circuit. This system is not feasible for general pipeline use because of length of required leads and switching of one or more distant rectifiers. The system works well where the protected structure is relatively compact such as subsurface tanks, exterior tank bottoms, interiors of water tanks, oil or water well casings, short pipeline sections, and most marine installations.

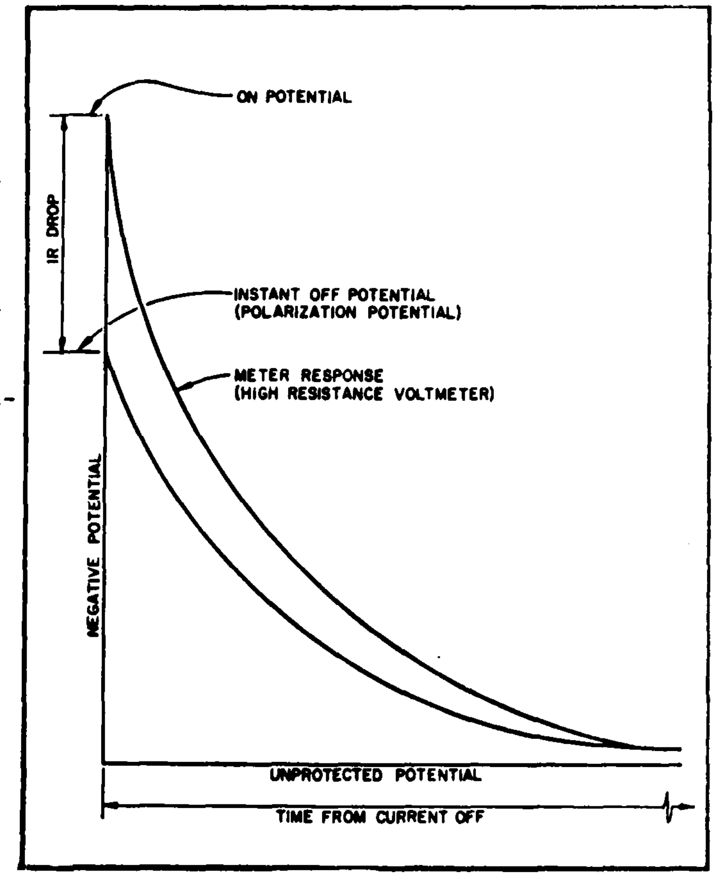


Figure 98. Potentials related to time on interruption of cathodic protection current.

As mentioned before, the time between interruption of current and measurement of potential should be as short as possible. Actual time before significant loss of polarization can vary from fractions of a second to hours. Any factor that quickly removes products of the cathodic reaction will accelerate depolarization. All things considered, current interruption, if done properly, gives the simplest and most reasonably accurate correction for IR drop. At least one supplier provides an electronic system for current interruption using a very short interruption time interval.

For general pipeline use where two of more rectifiers are used, synchronous interrupters are required. Usually two such interrupters for adjacent rectifiers will provide sufficiently accurate *OFF* potential data. Interrupters using quartz timing are available, providing for accurate synchronization. A timing interval of 25 seconds *ON* and 5 seconds *OFF* usually will be satisfactory for pipeline work.

A possible source of error when measuring substructure potentials could be IR drops caused by presence of stray currents of unknown magnitude in the contacting electrolyte. The best protection against such error is to place the reference electrode as close as possible to the structure under test.

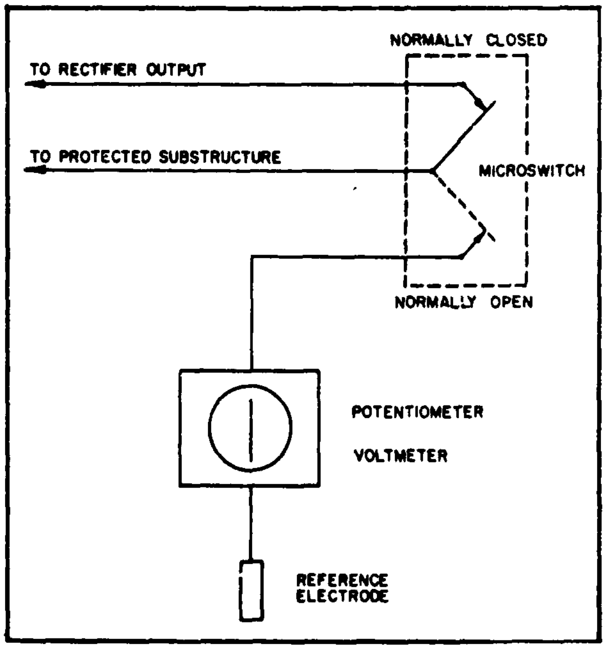


Figure 99. Circuit for *off* potential measurement.

To summarize briefly, a cathodically protected substructure potential to copper sulfate electrode of -0.85 volt or more indicates that protection exists under the following conditions:

(1) If substructure is immersed in seawater or similar electrolyte, with rectifier on and reference electrode contacting electrolyte within 1.5 meters of substructure; or

(2) if substructure is buried in soil with rectifier output momentarily interrupted and reference electrode contacting soil above or immediately adjacent to substructure.

c. Design.

(1) General. Ideally, design for cathodic protection should be a part of the original design of the substructure. Placing an existing substructure under cathodic protection, if installed without cathodic protection considerations, can be expensive. Some measures to ensure low cathodic protection current requirements that should be included at the design stage of subsurface structures are:

(a) If coating is feasible, use a high quality coating and apply properly with minimum bare areas or discontinuities (holidays);

(b) provide electrical isolation for large bare metal areas, if not to be protected, such as steel bulkheads, tank bottoms, electrical grounding systems, and local utility piping; and

(c) be sure that there are no metallic contacts with other subsurface structures such as pipelines, pipeline casings, or cables.

A very important part of cathodic protection design is to check carefully for presence of other subsurface structures in the area that are not to be protected or are owned by others. These are usually known as "foreign" substructures and they may suffer from a side effect of cathodic protection known as interference. The point to emphasize here is that a proposed anode installation should not be placed closer than 90 meters from an existing foreign substructure, either in soil or in water. This applies particularly to a proposed impressed current anode installation. Also check carefully for location of other cathodic protection systems in the area, especially locations of anode beds.

(2) Anode Choice. Whether to use galvanic anodes or impressed current anodes to protect a given substructure normally will depend on three factors, singly or in combination:

(a) Amount of protective current required,

(b) resistivity of the contacting electrolyte (soil or water); and

(c) electrical power availability.

Current requirement can be calculated or, preferably, determined by actual test. If calculated, the total exposed area in square meters must be determined. If the substructure is bare steel in normal soil or normal quiescent fresh or brackish water, a current density requirement of 10 milliamperes per square meter may be assumed. Total current required in amperes would equal total exposed area in square meters multiplied by 0.01. If all or part of the exposed steel is coated, an assumption of coating quality must be made. For good quality, relatively undamaged coating, it is customary to assume that the substructure is 1 percent bare for the coated part and figure the total current requirement accordingly. Thus, a coated substructure will require far less current for protection. The main difficulty with calculating current requirements is that the 10 milliamperes per square meter figure for bare steel may vary over a wide range, especially in moving water where it is almost always higher, sometimes by orders of magnitude. This is why an actual test for current requirement is preferable to reliance on calculated values.

Resistivity of the electrolyte (soil or water), in ohm-centimeters, should be determined by measurement using the Wenner four-point method. Resistivity is a measure of electrolyte resistance to current flow. The higher the resistivity, the lower the output will be from a galvanic anode, and the higher will be the voltage required to produce necessary current from an impressed current anode. Reported resistivity of an area should be an average of a number of measurements made at various locations in the area. Measurements should be made by a person qualified by experience in resistivity measurement for cathodic protection work. Table 56 shows electrolyte resistivity and IR drop for bare pipe.

Electrical power may be provided from several sources. Commercial alternating current power is the most widely used and has the lowest cost. Other sources are solar power (increasing in use as costs come down), thermoelectric, engine-driven generator, and windpower. Power availability

may be the deciding factor (along with resistivity) in an anode-type choice.

As discussed in an earlier section, galvanic anodes installed in soil environment should normally be completely surrounded by chemical backfill. This is to provide uniform low resistance to the soil. Galvanic anodes installed in water do not require any backfill as the water will provide uniform contact with the anode. Impressed current anodes in soil also require backfill but for different reasons. Here the backfill material is carbonaceous in nature. The anode makes electrical contact with the backfill. Ion transfer, with resulting loss of material, occurs at the backfill interface with the soil. This results in longer anode life and lower contact resistance as the backfill is of low resistivity and much greater surface contact area with the soil than would be possible with the anode alone. As with galvanic anodes in water, impressed current anodes in water do not use backfill.

(3) Calculating the Resistance of a Single Anode. Anode installation design requires that the effective resistance of the anode (or anode bed) to its environment be known or be calculated. Dwight's equation is generally used for single galvanic or impressed current anode resistance determinations in either water or soil. The equation is

$$R = \frac{\rho}{2\pi L} \{(\log_e \frac{4L}{a}) - 1\} \tag{1}$$

where

R = resistance of vertical anode or backfill to ground or water in ohms

L = length of anode in centimeters

a = radius of anode in centimeters

ρ = electrolyte resistivity in ohm-centimeters

This can be simplified to:

$$Rv = \frac{0.012\rho}{L} \log \left(\frac{35.3L}{D}\right) \tag{2}$$

where

Rv = resistance of vertical anode or backfill column to ground (soil or water) in ohms

L = length of anode or backfill column in feet

D = diameter of anode or backfill columns in inches

ρ = electrolyte resistivity (backfill, soil, or water) in ohm-centimeters

(a) Anode Installed in Backfill Soil. If a single anode is to be used, in soil, the internal resistance (anode to backfill) should be considered. Internal resistance is not a factor when the anode is installed

without backfill, such as in seawater. This will depend on the type of backfill used which will, in turn, depend on whether the anode is to be of galvanic or impressed current type. For an impressed current anode with carbonaceous backfill, a backfill resistivity of 50 ohm-centimeters may be used. Assume a graphite anode 7.6 centimeters (3 inches) in diameter and 1.5 meters (5 feet) in length is to be centered in a vertical backfill column 20.3 centimeters (8 inches) in diameter and 2.1 meters (7 feet) in length (see Fig. 100). Resistances are calculated for the anode and for the backfill column using equation (2) with ρ = 50 ohm-centimeters. The difference between the two values represents the internal resistance of the anode (0.213 - 0.128 = 0.085 ohm). For most conventional impressed current anodes used singly, a figure of 0.1 ohm may be safely used. Where more than one anode is to be connected in parallel, the internal anode resistance for the group becomes the single anode internal resistance divided by the number of anodes in the group. If the number of anodes to be parallel connected is more than three or four, the internal resistance becomes negligible. The same method is used to calculate the internal resistance of a single galvanic anode (see Fig. 101). Here the backfill resistivity will be higher, with a resulting higher internal resistance.

(b) Anode Installed in Water. For suspended vertical anode installations in water, the anode should be installed so that the top of the anode is never less than 1.5 meter (5 feet) below the water surface. Refer to tide data. The bottom of the anode should be 1.5 meters above the channel or marine bottom. Header cables should be far enough above the water surface to ensure no water contact. In protected areas this would be a minimum of 3 meters (10 feet). Header cables would have to be at much greater height for open-sea areas. This will require anodes with leads large enough to permit connection to the header cable with no underwater splicer required. In some cases anodes may require installation in perforated nonmetallic pipe to prevent damage by water movement.

(4) Calculating the Resistance of Anode Groups. Usually anodes will be used in groups, installed in a line, connected in parallel to a header cable which in turn is connected to the substructure to be protected (galvanic anodes) or to the positive output of the power source (impressed current anodes). A calculation of the overall resistance of the parallel-connected group (usually termed "anode bed" or "ground bed") will be required. The effective resistance of the group, differing from normal parallel electrical circuits, will not be equal to the resistance of one anode divided by the number of anodes in the group. This applies to marine installation also. Due to mutual interference between anodes the resistance of the group will always be higher than that determined by parallel electrical circuit calculations, varying with the number of anodes, anode spacing, and electrolyte resistivity. Several methods have been used for the calculation of parallel anode resistance. One method utilizes the following equation:

$$Rv = \frac{0.001566\rho}{NL} \left\{ \left(2.303 \log \frac{2.94\ L}{D}\right) + \left(\frac{2\ L}{S}\ 2.303 \log 0.656\ N\right) \right\} \tag{3}$$

where

Rv = resistance to electrolyte (soil or water) in ohms of the vertical anodes in parallel

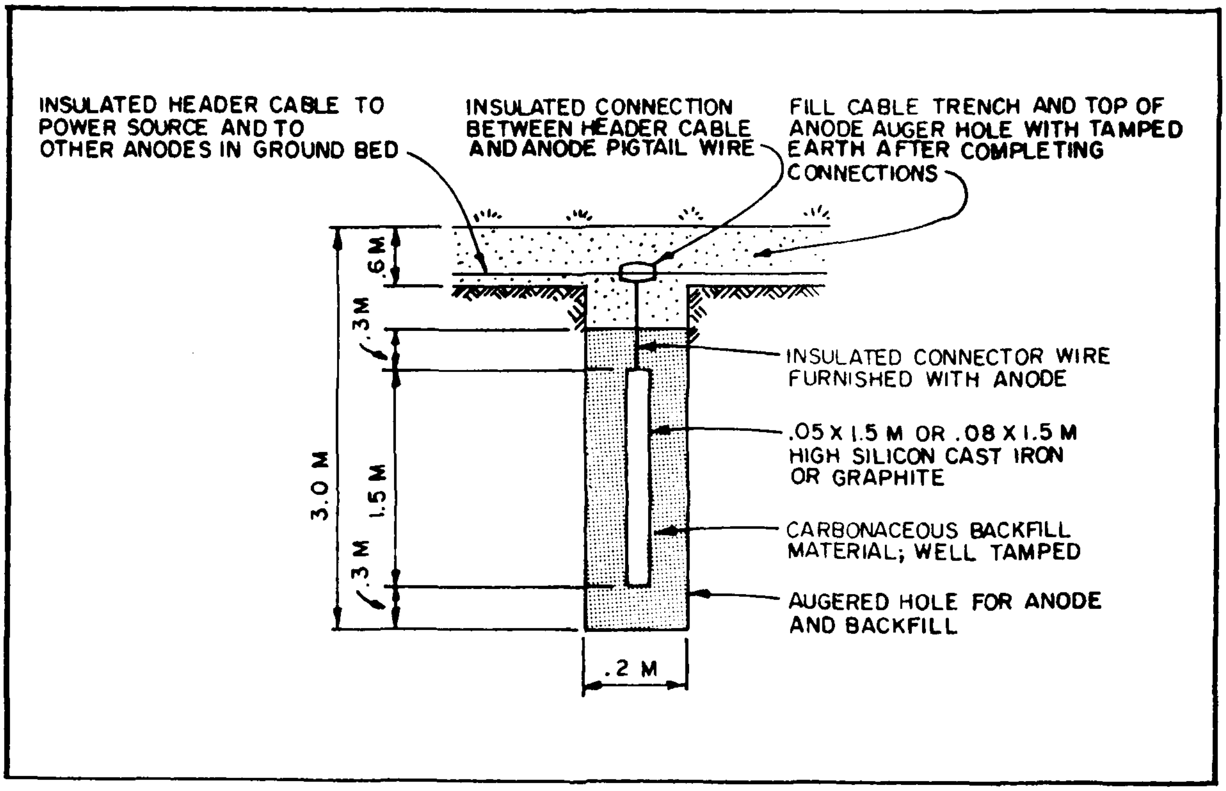


Figure 100. Anode in carbonaceous backfill.

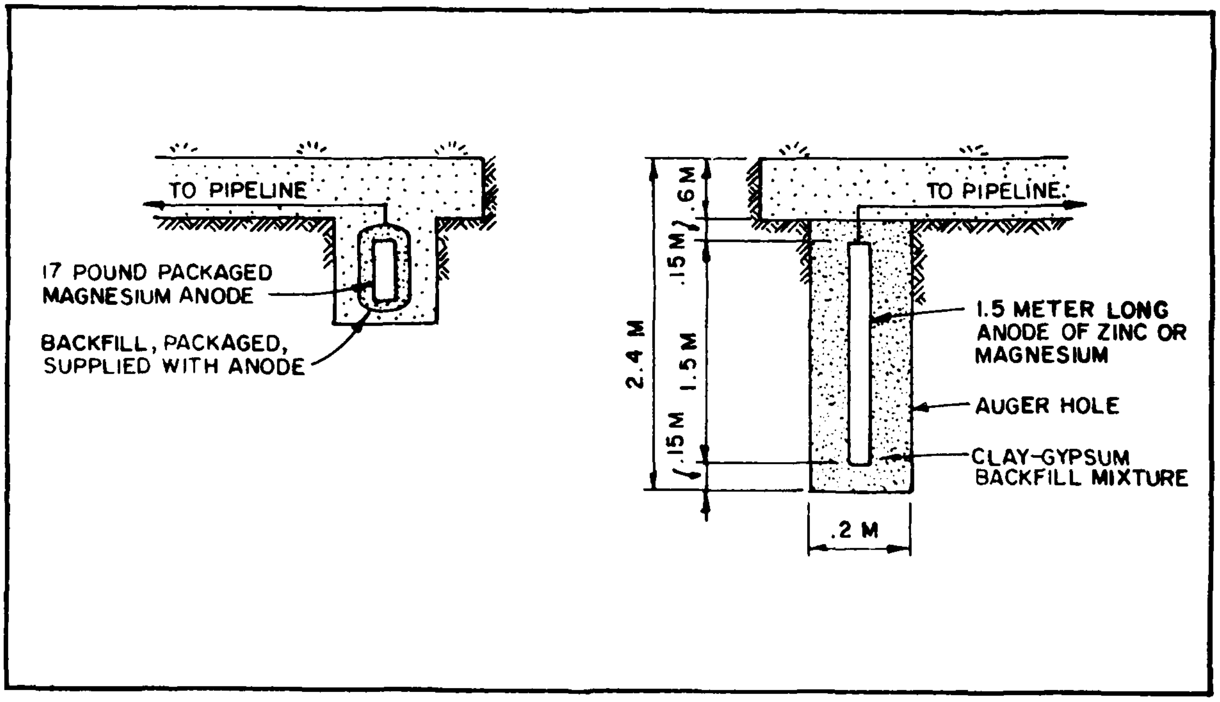


Figure 101. Anodes in other backfill materials.

ρ = resistivity of electrolyte in ohm-centimeters

N = number of anodes in parallel

L = length of anode (or backfill column) in meters

D = diameter of anode (or backfill column) in meters

S = anode spacing in meters

The resistance of the anode group is the sum of Rv and the internal resistance of the group, that is, the internal resistance of a single anode divided by the number of anodes in the group.

Equation (3) may be used to construct a chart for use with the anode size and backfill size to be used for a particular project. Such a chart, based on impressed current anodes 0.05 meter (2 inches) in diameter and 1.5 meters long in 0.2-meter (8 inch) by 2.1-meter (7 foot) backfill columns of 50 ohm-centimeters resistivity, is shown in Figure 102. A similar typical design chart for galvanic anodes is shown in Figure 103. Note that both charts are based on electrolyte resistivity of 1 000 ohm-centimeters. Anode (or backfill column) resistance to electrolyte is directly proportional to electrolyte resistivity. For example, consider 15 anodes in parallel at 7.6 meters (25 feet) spacing in 2 200 ohm-centimeter soil. Anode (in backfill) resistance in 1 000 ohm-centimeter soil, shown on the chart in Figure 103, is 0.233 ohm. Resistance in 2 200 ohm-centimeter soil = 0.233 x 2 200/1 000 = 0.513 ohm. To this add the internal resistance of the group. From use of equation (2) the internal resistance of one electrode is 0.106 ohm, making the internal resistance of the group (0.106/15) = 0.007 ohm, a negligible amount. The total resistance is 0.520 ohm, but 0.513 ohm could be used safely.

(5) Calculating Resistance in Cables. Cathodic protection design also requires a knowledge of the resistance of various sizes of copper wire or cable most often used in anode installations. Resistance data and common use of some of the most commonly used sizes are shown in Table 57.

(6) Calculating Anode Lifespan. If current output of a galvanic anode of any given weight is known, its approximate useful life can be calculated. The calculation is based on the theoretical ampere hours per newton of the anode material, and its current efficiency (see Table 52). Also involved is a utilization factor, which may be taken as 85 percent. This means that when the anode is 85 percent consumed it will require replacement. This is because there is insufficient anode material remaining to maintain a reasonable percentage of its original current output.

Expressions for determining individual anode life for different materials are presented below with efficiency and utilization factors expressed as decimals:

(a) For magnesium:

$$\text{Life in Years} = \frac{0.026 \cdot \begin{array}{c}\text{anode weight}\\ \text{in newtons}\end{array} \cdot \text{efficiency} \cdot \text{utilization factor}}{\text{anode current in amperes}}$$

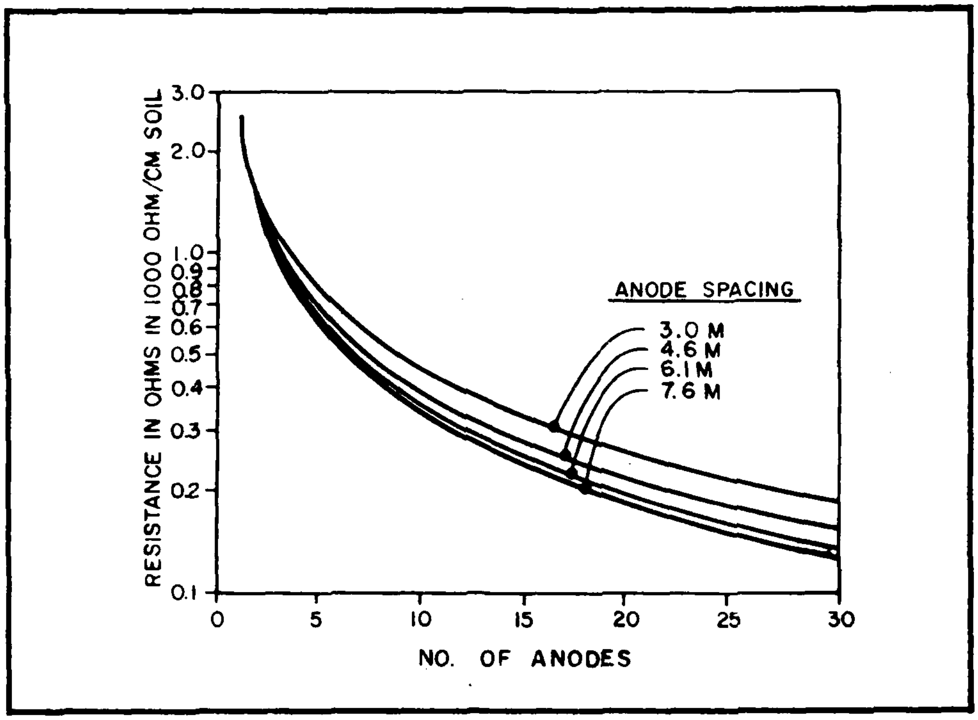


Figure 102. Chart of anode spacing (impressed current method).

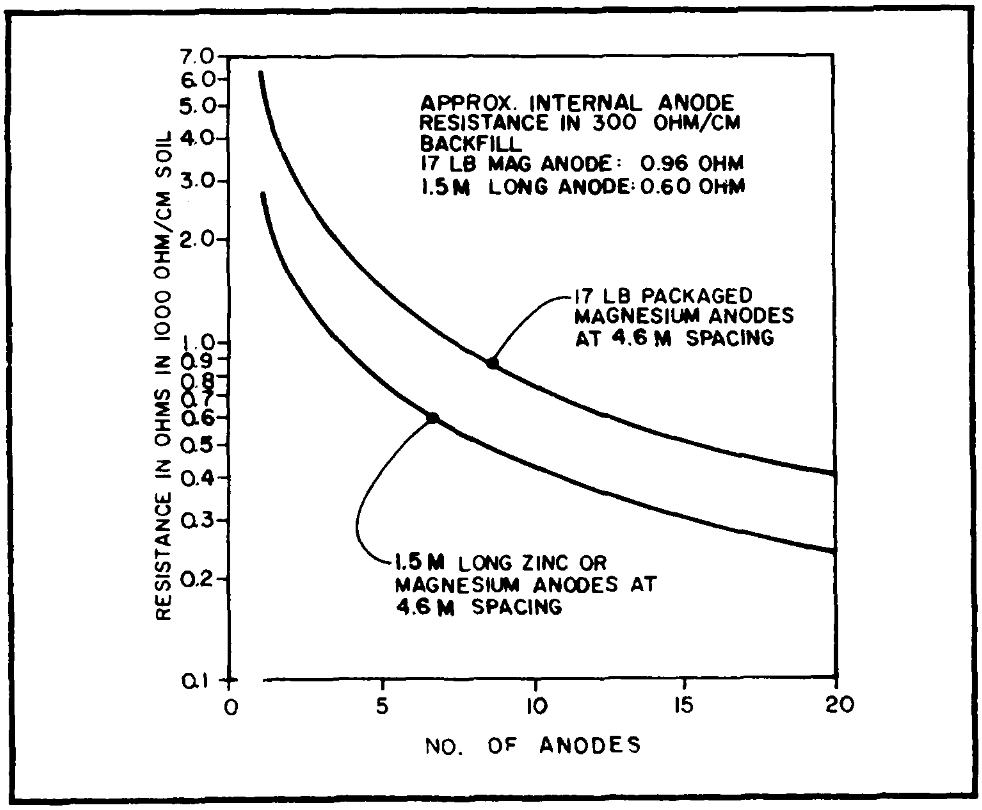


Figure 103. Chart of anode spacing (galvanic anode method).

Table 57. Copper wire resistance.

Common Use	Wire Size (AWG)	Resistance of standard copper wires in milliohms (ohms times 10^3) per meter at 25°C (77° F)
Impressed Current Anode Installations	4/0	0.167
	3/0	0.211
	2/0	0.266
	1/0	0.335
	1	0.423
	2	0.531
	4	0.850
	6	1.35
Galvanic Anode Installation	8	2.15
	10	3.41
Substructure Test Stations	12	5.41
	14	8.60
Instrument Test Leads	16	13.7
	18	21.9
	20	34.8
	22	55.8

Temperature Correction Factors

Temperature °C	Temperature °F	Multiply Resistance at 25°C by:
0	32	0.901
10	50	0.941
20	68	0.980
25	77	1.000
30	86	1.020
40	104	1.059

(b) for zinc:

$$\text{Life in Years} = \frac{0.009\,5 \cdot \text{anode weight in newtons} \cdot \text{efficiency} \cdot \text{utilization factor}}{\text{anode current in amperes}}$$

(c) for aluminum (Galvalum II alloy) in seawater:

$$\text{Life in Years} = \frac{0.035 \cdot \text{anode weight in newtons} \cdot \text{efficiency} \cdot \text{utilization factor}}{\text{anode current in amperes}}$$

Using the values from Table 52 for theoretical ampere hours per newton and current efficiency, along with an 85 percent utilization factor for the three anode materials, the above expressions may be simplified to:

$$\underline{\text{Magnesium}} \qquad L = \frac{1.105\ W}{I} \cdot 10^{-2} \tag{4}$$

$$\underline{\text{Zinc}} \qquad L = \frac{0.767\ W}{I} \cdot 10^{-2} \tag{5}$$

$$\underline{\text{Aluminum}} \qquad L = \frac{2.826\ W}{I} \cdot 10^{-2} \tag{6}$$

where L is the anode life in years, W the anode weight in newtons, and I the anode current in amperes.

As may be noted, Equations (4), (5), and (6) may also be used for calculating anode bed life where L is the anode bed life in years, W the total anode weight in newtons (all anodes), and I the anode bed current in amperes.

(7) Deep-Well Anode Beds. Some mention should be made regarding deep-well anode beds, as in recent years they have attracted much interest for impressed current systems, primarily on pipelines. Such installations can be very useful if conditions permit. In the case of pipelines the well may be in the pipeline right of way, avoiding the requirement for additional right of way for conventional surface type anode beds. A deep-well anode bed, usually 60 to 120 meters (200 to 400 feet) in depth, can be described as one in which the anodes are placed in remote earth by drilling straight down or by using an existing hole such as an abandoned water well. For pipelines this accomplishes the same general result obtained by locating a conventional surface type anode bed laterally several hundred feet from the pipeline. Advantages of a deep-well anode bed include small surface space needed (little or no additional right of way), probably less interference problems, and frequently lower anode-to-soil resistance than with conventional anodes. Disadvantages include great difficulty or impossibility of repair, necessity to prevent contamination of underground potable water sources, difficulty in determining soil resistivity at depths of several hundred feet, and expense of installation.

(8) Application of Calculation Methods. With the preceding background on design considerations, some examples follow to show how designs may be worked out for several types of subsurface structures. Professional consultation is advisable before finalizing plans for any cathodic protection installation. Each location has specific problems which must be recognized and considered if the installation is to be effective and reasonably trouble free.

c. Example Project. A part of the waterfront facility consists of a steel sheet-pile bulkhead (see Fig. 104 for cross section). It shows a typical seawater cross section, illustrating the various zones of exposure. The waterside of the bulkhead should be provided with cathodic protection as soon as possible to prevent further loss of steel caused by the corrosive action of the contacting seawater. Average water resistivity is 20 ohm-centimeters. The soil side of the bulkhead is also to be provided with cathodic protection at an early date. Average soil resistivity is 500 ohm-centimeters. A minimum of 20 years life for the waterfront facility is anticipated.

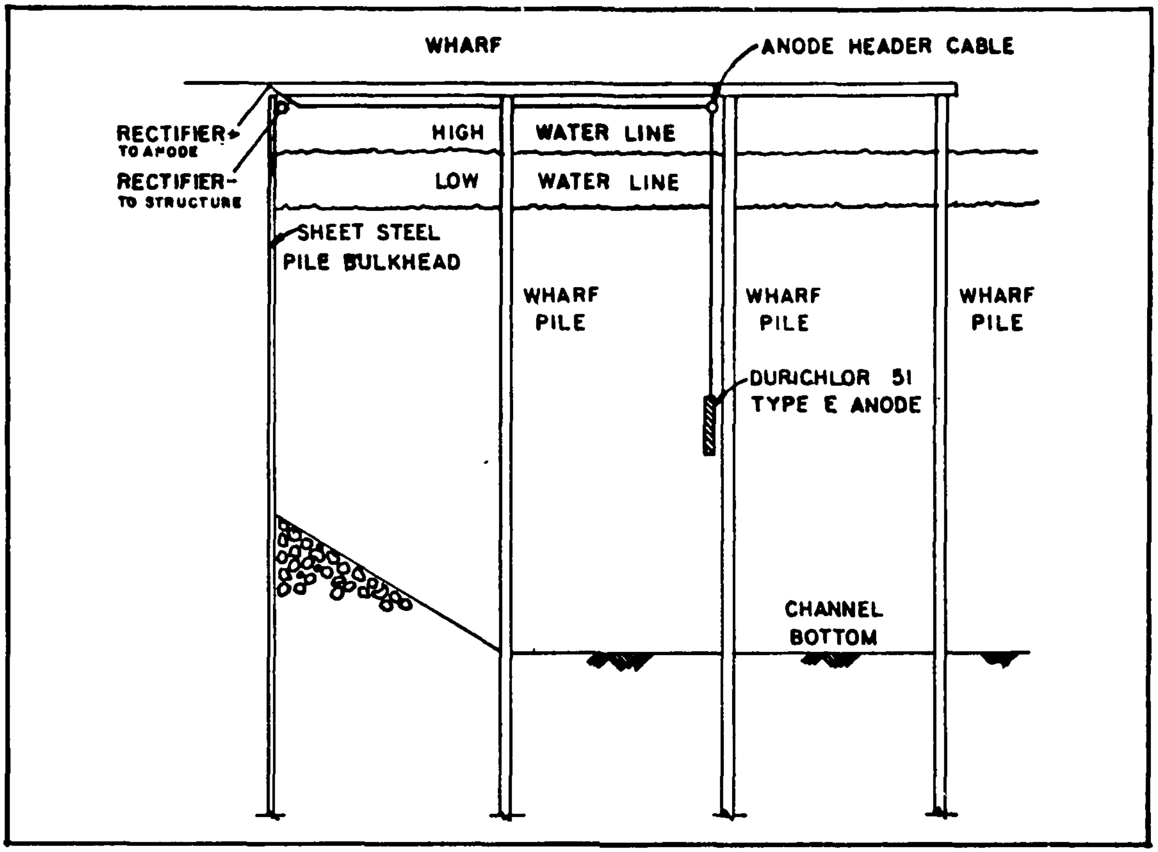


Figure 104. Cross section of wharf used in example.

(1) Conditions. The steel sheet-pile bulkhead is 300 meters (980 feet) in length. There are approximately 9 meters (30 feet) of water-exposed steel or 2 700 square meters (29 000 square feet) including a two-foot splash zone and about 3 000 square meters (32 300 square feet) embedded in the sandy clay soil. The steel surface contacting the water is expected to require about 55 milliamperes per square meter (5.1 milliamperes per square foot) for protection. The embedded part, 3 000 square meters is expected to require about 22 milliampere per square meter (2.0 milliamperes per square foot) for protection.

(2) Calculations. Current requirement:

2 700 square meters @ 55 milliamps per square meter = 149 amperes.
3 000 square meters @ 22 milliamps per square meter = 66 amperes.
Total current required = 215 amperes.

(3) Resistance. Anodes used will be Durichlor 51 Type E, 7.6 centimeters (3 inches) in diameter, 1.5 meters (60 inches) long, to be suspended in the water under the wharf using polypropylene rope. These anodes are rated at 4 amperes per anode for long service life.

$$\frac{215 \text{ (amperes required)}}{4 \text{ (amperes per anode)}} = 54 \text{ anodes}$$

For safety margin use 60 anodes, spaced evenly under the wharf, about 5 meters (16 feet) apart. Using equation (3) the anode resistance of each component of the example project is calculated to determine the total anode resistence:

60 anodes, averaging 20 ohm-centimeters resistivity	= 2 milliohms.
Rectifier positive to center of header cable under wharf: 30 meters No. 4/0 copper cable in conduit	= 5 milliohms
Rectifier negative to bulkhead: 30 meters No. 4/0 copper cable in conduit	= 5 milliohms
Header cable under wharf, center connection, effective length, 155 meters No. 1/0	= 51 milliohms
Bulkhead resistance is negligible.	
Total resistance	= 63 milliohms

(4) Voltage Requirement. Required rectifier voltage is obtained using Ohm's Law: $E = IR$ or required voltage is equal to total current multiplied by total circuit resistance or $E = 215 \times 63 = 13\ 500$ millivolts (13.5 volts). For best results, a current and voltage requirement test should be made after the anode installation is complete, including the cables to the rectifier location. A direct current welding generator capable of furnishing the above current and voltage should be used. For test purposes, complete polorization is not required. However, current should be applied for several days, with potential measurements made from bulkhead to a reference electrode in the water within 1.5 meters of the bulkhead (to minimize IR drop in the readings) at several locations and at several depths, from surface to bottom. Readings of -0.85 volt to a copper sulphate reference electrode or -0.84 volt to silver-silver chloride reference electrode indicate adequate protection.

(5) General. Some comments should be made regarding the example. A continuous 25-millimeter-diameter steel rod should be welded in place in two locations to each sheet pile for the full length of the bulkhead. This connection rod should be well above the splash zone and should be well coated to ensure permanent connections. Woven grounding straps bolted to the sheet pile may also be used, if they are protected against the environment. The point must be made that the connections must be flexible. A sheet-pile bulkhead may deflect enough to break welds to a rigid 25-millimeter (1 inch) steel rod. Electrical continuity to each and every sheet pile is essential for the success of the cathodic protection system.

Care should be taken to ensure that the steel bulkhead is electrically isolated (insulated) from all other structures or piping. Again, this is essential if the protected installation is to remain reasonably trouble free.

4. Cathodic Protection and Coatings in Combination.

A combination of cathodic protection and coatings provides the advantages of both. Protective coatings are known to be the primary considerations

for protecting steel. Cathodic protection is needed as backup in areas where the continuity of the coating is affected, due to damage or application problems. If no coatings were used, the cost of cathodic protection would be greatly increased, both in terms of (1) equipment needed and (2) current required for protection of a bare (noncoated) structure. Examples of structures where cathodic protection is used in conjunction with coatings include: sheet piling, production platforms, piles, docks, and similar structures continuously immersed in water.

In these instances, the protective coating must possess:

(a) Good dielectric strength,

(b) good alkali resistance,

(c) good adhesion characteristic,

(d) low moisture absorbtion and transfer rates,

(e) good coating thickness, and

(f) resistance to the passage of ions.

Carefully conducted tests and field use show that most coatings designed for immersion in seawater which have the properties described above will perform satisfactory at steel potentials ranging from -0.8 to -1.3 volts with respect to a copper/copper sulfate reference cell. Above the 1.3-volt potential many coatings will show degradation such as cathodic disbondment.

If a good coating can be applied to both sides of the bulkhead pile sheets before installation, cathodic protection current requirements would be decreased drastically. The coating, if applied, should be as good as the state of the art permits, such as white metal sandblast, inorganic zinc primer, followed by two coats of coal-tar epoxy, for a dry film thickness of at least 0.41 millimeter (16 mils). In any event, the piling, after installation, should receive such a coating from the low water line upward through the splash zone to the top of the bulkhead. Any cathodic protection is marginal above the low water line and nonexistent in and above the high water line.

5. Marine Exposure.

The characteristics of coating systems and structure material to be protected, as well as the specific marine exposure, will determine which coating systems can be effectively used. The specific marine exposures must be carefully considered when selecting a coating system to achieve good structure protection. Marine exposures are generally considered to be marine atmosphere, splash and spray zone and submerged zone. More than one of these exposures may occur on any single structure.

For example, a marine atmosphere is one which carries airborne salt. Since only pure water evaporates from a body of saltwater, this physical process does not put salt into the air. Instead, salt becomes airborne only under conditions in which finely divided saltwater droplets (spray and

mists) are projected into the air by wind and wave action. These fine droplets may remain as such for some time, or the water may evaporate, leaving a tiny, solid particle of salt. Wind may carry the droplets or the salt particles some distance from the point of origin. It will be seen, therefore, that the term marine atmosphere is not a precisely definable exposure condition. The term might be applied to any situation where the salt content of the air is great enough to exercise some effect on corrosivity and on protective coating performance. The produced effects may range from very intense to near zero. The concentration of airborne salt, both close to the shoreline and at increasing distances from it, is difficult to even generally predict, since shoreline topography, wave heights, prevailing wind direction and velocity, and inland physical features are all important factors. However, the intensity of the corrosive effect declines rapidly as the distance from the shore is increased and in most cases, supposed acceleration of corrosion many miles inland is largely imaginary. It has been reported that the effect of marine spray is negligible at distances 3 kilometers (2 miles) inland and that analysis of iron corrosion products at seaside towns usually shows more sulfur (from industrial contamination) than chloride (from salt spray).

There is no doubt, however, that steel surfaces subject to atmospheric exposures that are intensely marine in character present protection problems which are not solved by surface preparation and paint coatings customarily used for inland structures. The effects introduced by the salt are manifold and varied. An obvious effect is that the corrosion-accelerating influence of the salt causes even the smallest discontinuity and thin spot in the coating to become a focal point for rusting which rapidly enlarges the original corrosion site. This effect is heightened by the fact that the corrosion products (rust) formed in salt-bearing atmospheres do not exert a protective influence against further corrosion to the degree that they do in inland locations; i.e., corrosion continues at a high level in marine atmospheres, whereas the rate usually drops off considerably in most inland atmospheres. The electrochemical reactions involved in the salt-accelerated corrosion processes result in alkalies and other products which may be both harmful to the paint film itself and to adhesion of the coating to the metal.

The net effect of the presence of even small amounts of deposited salt is to increase the need for more care in surface preparation and paint application; in more severe cases, it brings about a need for a more resistant coating system than is customarily used on inland, weather-exposed steel. The need for thoroughness in surface preparation and paint application cannot be overemphasized. This need is increased by the fact that crevices, joints, junctions of joining members, interior angles, pockets, undersides of horizontal and inclined members, and similar surfaces tending to be protected from the direct action of rain which would wash away the salt, are the places of greatest corrosion and are also the places which tend to receive the poorest paint job.

Structures exposed to moderate and moderately severe marine atmospheres should receive a more advanced paint system. Thorough inspection is probably at least as important as the proper choice of coating.

6. Uses in Coastal Structures.

Generally the generic coating systems discussed in this section have found satisfactory use in the exposures shown in Table 58.

Table 58. Typical uses of coatings.

Generic Type	Use
Alkyds	On metals in mild marine atmosphere.
Silicone Alkyds	On metals in mild marine atmosphere.
Acrylic (Solvent based)	On metals in moderately severe marine atmosphere.
Acrylic (Water Reducables)	On masonry, concrete and wood in moderately severe marine atmosphere.
Chlorinated Rubber	On metals in splash and submerged zones.
Coal Tar	
a. Mastics and Coal-Tar Cutbacks	Splash and submerged zones.
b. Modified Coal Tar	Splash and submerged zone.
Epoxies (Catalyzed)	Splash and submerged zone; has excellent toughness.
Epoxies - Phenolic	Splash and submerged zone but is brittle.
Phenolics	Heat cured; high corrosion resistance but brittle; used for tank linings.
Polyurethanes (or Urethanes)	Usually heat cured; splash and submerged zone; tough with high abrasion resistance.
Vinyls	Marine atmosphere, splash and submerged zones; poor solvent resistance.
Zinc (Inorganic)	Splash and submerged zone; used as single or multiple coat system.
Zinc (Organic)	Splash and submerged zone; generally the higher the zinc content the better the coating.
Underwater Coatings and Mastics	Good for in place structures in submerged structure.

XII. SUMMARY

1. General.

This section summarizes the principal properties and uses of materials in coastal structures, beach protection devices, and erosion control. Generally more than one material is used in a single coastal structure and compatibility and effectiveness of the materials working together must be considered in each case. The selection of materials for a specific coastal structure may require consideration of the cost of labor and availability in addition to the physical properties of the materials. Such considerations influence the design of structures when more than one material can be employed to perform the same job. By considering the properties of materials and their past performance experience, the coastal engineer may select the proper material to achieve his design objective. Material uses are generally considered first for their structural properties and then their durability in coastal structures. In addition to the detailed information given in the preceding sections, the general summary that follows may assist in the selection of materials.

Most, if not all, of the common construction materials have been used separately or in combinations of two or more in the creation of coastal structures. For example, breakwaters, both detached and shore-connected, are commonly constructed of earth and stone and in many instances capped with concrete armor units. To the commonly used earth and stone, steel and concrete sheet piles have been added from time to time for special functions. Also, asphalt has been used many times as an earth and rock binder for capping such structures and holding the basic materials in place. Bulkheads and retaining walls have been constructed of stone, sheet piles made of concrete or steel, mass concrete, and wood. Groins and jetties have been built of these materials as well.

Marine and harbor structures of more complex design usually require the use of a variety of materials in construction, the selection based not only on their physical properties but their availability at the site and ease of installation as well as economy of construction. When temporary structures are called for, recycled materials such as broken or crushed concrete, crushed asphalt concrete, blocks and salvaged or scrap metals (such as ships, barges, and railroad cars) have been used. The recent development of a large variety of synthetic materials has resulted in the production of improved coating systems and synthetic films for filter cloths as well as foams for improved buoyancy. The synthetic rubbers are used as energy absorbers in fender piles, bumpers and other protective devices.

Many materials, when used in coastal structures, require special treatment. Wood, for example, will have a substantially improved service life when properly pretreated with creosote and other preservatives. Metals, and more specifically steel, will require protective coatings or cathodic protection (usually both) to be durable in the coastal environment.

2. Materials.

a. Stone.

(1) Properties. Stone refers to individual blocks, masses, or fragments that have been broken or quarried from bedrock exposures, or are

obtained from boulders and cobbles in alluvium. Crushed or broken stone includes all stone in which the shape is not specified. Stone for coastal structures should be free from laminations, weak cleavages and be of such a character that it will not disintegrate from the action of air, seawater, or handling and placing. A stone of high specific gravity is desirable because it increases the resistance to movement by the action of waves or currents. Durability of stone can be affected by its mineral composition, texture, structure, hardness, toughness and resistance to the effects of wetting and drying and freezing and thawing. Stone is generally classified as granite, basalt and related rocks, limestone and marble, sandstone and miscellaneous stone.

While no standard testing procedure has yet been developed for the determination of the quality of stone, other than past experience with specific quarries, there are testing programs that are used. With any testing program for the determination of the quality of rock, judgment is necessary in applying and interpretating test results. This requires a great deal of experience and should be left to geotechnical experts. Any test program should include petrographic examination, determination of absorption and bulk specific gravity (ASTM Standard C97-47 or C127-77), a soundness test (AASHTO T-104-46 or ASTM C88-76) and an abrasion test (Los Angeles rattler, Wetshot rattler or ASTM 535-69 {75}). Other tests may prove useful depending on specific project requirements. Properties contributing to durability of stone may be both physical and chemical and chemical changes can best be evaluated by experts.

(2) Stone Size and Shape. Stone size is important in coastal structures. Bedding layer material, core rock or quarry-run material is usually 15 to 20 centimeters (6 to 8 inches) or less. Underlayer stone may range from a few kilonewtons to about 30 kilonewtons. Armor stone is the largest size and ranges up to 220 kilonewtons. Stones larger than about 220 kilonewtons are generally not easily handled. While the three ranges of stone sizes are required for the different parts of a rubble-mound structure, an adequate number of classes within each range is also necessary. In fitting stones into a structure, the shape as well as the size is important. Design requirements usually specify that the greatest dimension of an individual stone be no more than three times its least dimension.

In addition to the physical properties of stone, the method of quarrying will also determine the size, range and classes within a size range that are produced. Depending on the area topography, a quarry will generally be developed as either a side hill or a pit-type operation. The size of quarry face developed in any given operation is usually determined by the thickness of the formation. The method of blasting and the type of explosive, as well as the geological and physical characteristics of the material, will determine the degree of fragmentation that will result from the quarry operation. Generally a high powder factor (quantity of explosive per unit volume of rock) will produce a greater degree of fragmentation than will a lower powder factor. Also, greater fragmentation will be achieved in a massive rock by using a large number of small diameter holes at close spacing than by using large diameter holes at greater spacing. It also appears that best fragmentation is achieved when holes are detonated individually rather than simultaneously.

(3) Use in Coastal Structures. Stone has many uses in coastal structures, including offshore structures, shore-connected structures, and anchors. Breakwater, jetty and groin design often include several sizes of stone for use in the core and underlayers and for use in the covering or armor layer. Seawalls and revetments may also be constructed from stone. For protection of pier foundations a quarrystone blanket may be laid under the pier in the scour area.

b. Earth.

(1) Properties. Earth or soil is a large assortment of materials of various origins. For engineering purposes soils are generally classified as gravel, sand, silt, clay, and organic material; however, most soils are composed of a mixture of two or more of these materials. Although there are several soil classification systems, the most widely used in engineering is the Unified Soils Classification System (USCS). Gravel is usually considered to range in size from the No. 4 Sieve to 76.2 millimeters (3 inches). Gravels are cohesionless materials. Sand is defined as a grain size between 4.76 millimeters and 0.075 millimeter (No. 4 and 200 sieves, respectively) and sands may be further classified as coarse, medium, or fine. Sands are normally cohesionless materials; however, they present an apparent cohesion when damp or moist due to the surface tension effects of pore fluids. Silts and clays are known as fine-grain materials. Silts may also have an apparent cohesion but have relatively poor strength characteristics, limiting their use to certain cases. Clay materials are largely cohesive, have strength characteristics dependent on past stress history, and may be difficult to compact at high moisture contents. Minerals included in the clay composition influence the properties of the soil. Organic materials, formed by the decay of vegetable matter can be entrained in soils and usually have a spongy nature and a fibrous texture. Usually organic soils have high moisture and gas contents and a relatively low specific gravity.

The major significant engineering properties of soil are shear strength, compressibility, and permeability. The types of problems encountered in the design of coastal structures which utilize these characteristics are slope stability, bearing capacity, settlement, and erosion. Other useful properties of soils in the design of structures include dry density, water content, specific gravity, resistivity and corrosion potential, grain-size distribution, plasticity characteristics, chemical properties, and durability.

(2) Soil Placement Methods. Soil placement methods are usually determined by the fill location, underwater or above water, and the need for some degree of compaction. Earthfills made from land are usually truck-dumped and bulldozed into place while waterside delivery may be by barge or hydraulic pumping. Fill compaction above the water can be accomplished using mechanical equipment. A fill placed under water will usually require some form of superimposed loading for a period of time to compact it. This loading time depends upon the depth of fill and amount of loading. It usually varies from 0.5 to 2 years. The compactibility of the soil will also impact the loading time.

(3) Use in Coastal Structures. Earth is commonly used in virtually any port or harbor development, land reclamation, or coastal protection structure. In addition to fill of all kinds, earth is used in making soil-cement as well as fill material for plastic bags and other containing units.

c. Portland Cement Concrete.

(1) General. Concrete is used as unreinforced or mass concrete, as steel reinforced concrete or as prestressed or posttensioned concrete. The latter types are usually made in the form of precast structural elements. Specific properties of concrete may be modified and improved by the addition of admixtures for special purposes and to accommodate placing and installation requirements. The specific use of concrete in any structure will determine the mix design and curing process necessary to obtain a satisfactory result. Experience or consultation with experienced designers of concrete structures is necessary to ensure a durable concrete appropriate to the needs of the structure.

Durability is generally a requirement in coastal structures and the designer and constructor share the responsibility for creating structures which will function as designed over the anticipated life of the structure. Such structures have a high resistance to the disruptive attack of most environments including saltwater, alkalis, most acids, corrosive atmospheres, freeze-thaw cycles, and marine flora and fauna. Good concrete is also highly resistant to abrasion.

Failures of concrete structures have been studied and some of the more common causes of failure and methods of prevention are discussed in Section V. Determination of the cause of structural failure requires a careful analysis of the site conditions, the concrete ingredients, and the original design criteria by experienced professional engineers. Concrete failures usually are the result of the selection of the wrong type of cement, unsound aggregate, contaminated mixing water, improper admixtures or an inadequate curing process. With all these possibilities for creating poor concrete the design engineer must also have experience and good judgment in preparing plans and specifications to ensure that concrete is used within its physical capabilities.

(2) Uses in Coastal Structures. Thousands of marine structures have been satisfactorily designed and constructed of concrete with a long history of excellent performance. Because the resources required to make good concrete are generally available in all regions of the world, concrete has wide application for use in coastal and waterfront structures. Its successful use in seawalls, bulkheads, revetments, groins, jetties, breakwaters, and a variety of other structures over many years is evidence of its excellent properties for coastal engineering use.

d. Other Types of Concrete and Grout.

(1) Asphalt.

(a) General. Asphalt is a residue product from the refining of petroleum. It can be used alone as a membrane or coating or it can be mixed with other materials as a binder to produce mixes for a variety of purposes. Asphalt can be combined with sand and graded aggregate to form a voidless and impermeable asphalt concrete or with an open-graded aggregate to form a stable porous mixture. A composite asphalt structure can easily be constructed of different asphalt mixes with each layer performing a particular function. An example of this use might be an impermeable asphalt layer

supported by an open-graded asphalt drainage layer with an asphalt mastic placed with a screed over the compacted subsurface. The drainage layer serves to prevent damage to the watertight outer layer by draining away any seepage through the outer layer or any ground water intrusion.

The physical properties of asphalt alone are considered in its use in coastal structures in addition to its adhesive properties as a binder and its viscous properties under service conditions. The manner of asphalt placement as well as the service conditions will require certain minimum and maximum viscosities.

(b) Use in Coastal Structures. Engineers have made considerable use of asphaltic materials in the construction of many structures for coastal protection. Asphalt concrete is used to pave or revet the slopes and tops of earth or sand seawalls. It may also be used to pave, or cap, the top surfaces of quarrystone jetties, breakwaters, groins, and cellular steel breakwaters. Asphalt mastic mixtures are also used for grouting to fill-in the voids of quarry stone jetties and groins, and of the riprap facings of seawalls and revetted slopes. In foreign countries special equipment has been designed to place a sand-asphalt mastic under water in a continuous operation. The blanket is designed to prevent scour of large areas of the seabed. As more and more emphasis is placed on pollution control, engineers are finding that asphalt offers an economical and effective means of lining dredge disposal sites and waste storage areas that are sometimes necessary in the construction of coastal structures. Asphalt has an excellent history of performance in its use in coastal structures when properly designed and used in accordance with its physical properties and capabilities.

(2) Preplaced Aggregate and Grout. Portland cement grout poured in the voids of preplaced aggregate is a specialized construction method. It generally uses large stone with the voids filled with grout. It is a type of mass concrete used as a seawall or bulkhead. The physical properties as to durability, resistance to abrasion etc. are much the same as those of the stone and concrete components. One difference is in the cement grout mix design. Pozzolons and fluidizers are added to improve handling during placement and bonding to rock or old concrete.

(3) Portland Cement Grout. Portland cement grout will have the same physical properties as Portland cement concrete of similar mix design. Grout, however, is usually modified in its mix design because of its intended use and placement methods. This results usually in a grout mix of cement and water with sand. Very small gravel and clay, used as inert fillers, or even bentonite used as a stabilizer, may be added when it is placed under water. Grout is easily placed by pouring, pumping or injecting into place. In filling joints or narrow cracks it can usually be poured into place. In filling large voids or holes, pumping is a common procedure. When stabilizing ground beds for foundations or the area behind bulkheads to prevent leaching of the soil it may be injected into the ground or structure. This injection procedure may be the same as pumping but at relatively high pressure.

(4) Soil Cement. Soil cement is a mixture of pulverized soil and measured amounts of Portland cement and water compacted to a high density. The physical properties of soil cement are its high density as compared to uncemented soil and its rigidity, resulting in a structural slablike material

with the use of small quantities of cement. In good soils, 7-day compressive strengths of 2 070 kilopascals (300 pounds per square inch) are obtainable. Soil cement is used primarily as a base course for stabilizing and compacting soils for foundations, bank protection, and subbase construction. It has been used for earth dam cores, reservoir linings, and slope protection.

(5) Sulfur Cement. Sulfur cement concrete and grouts are a relatively recent development and as such do not have a long history of use in coastal structures. Recently, the availability of large quantities of sulfur has resulted in its increased use in construction projects as a binder or admixture of aggregates. Molten sulfur mixed with sand and aggregates produces a sulfur concrete of excellent strength.

Sulfur-asphalt binder materials have higher densities than normal asphalt as sulfur is about twice as heavy as asphalt. The sulfur-asphalt binder usually results in a lower void percentage than the asphalt cement without the sulfur addition. Sulfur does increase resistance to gasoline, diesel fuel, and similar solvents. It also improves stress fatigue characteristics. The finely dispersed sulfur particles add strength to impregnated fabrics.

Whereas sulfur cement materials reach their full strength quickly upon cooling, the inherent flammability and low melting point of sulfur impose some limitations on the use of sulfur cement. However, because of its quick-set characteristics, it may find many uses in emergency repairs that could have considerable longevity. With more experience and additional development, sulfur-cement products will probably find increased use in coastal construction.

e. Structural and Sheet Metals.

(1) Steel. Steel is the most utilized of all metals in marine service and for coastal structures. Carbon steel is an alloy of iron and carbon in which the carbon content is less than 2 percent. Structural steel limits the carbon content to less than 0.35 percent. Adding small amounts of alloying elements during the steelmaking process can improve the mechanical properties of steel as well as its corrosion resistance. Small additions of copper, nickel, chromium, silicon, and phosphorus have been effective in improving the corrosion resistance of steel.

In addition to its strength, the mechanical properties of steel of most interest in the design of steel structures are: ductility, brittleness, malleability, flexibility, hardness, resilience and toughness. Ductility is defined as the ability of a material to be drawn out without change in volume. Brittleness defines its lack of ability to be deformed without rupture. Malleability is the opposite of brittleness and refers to its ability to be forged or rolled into thin sheets. Flexibility describes its ability to bend under stress and return to its original shape when the load is removed. Hardness is a measure of its ability to resist indentation when subjected to impact. Resilience is its ability to absorb energy due to applied loads without breaking. Toughness indicates its ability to absorb large amounts of energy without rupture. Structural steel has a high degree of all these properties.

It is relatively easy to alloy other metals with iron in making steel. Low alloy steels contain up to 1.5 percent of elements such as manganese and silicon. Medium alloy steels contain 1.5 to 11 percent of alloy elements and high alloy steels, including both ferritic and austentic stainless steels, contain more than 11 percent of alloy elements.

Most coastal structures using steel as a principal construction material use certain steel shapes in the following manner:

(a) sheet piles for caisson walls, cutoff walls, bulkheads, and groins;

(b) "H" sections for bearing piles and beams;

(c) pipe or tubing for bearing piles, conduits and handrails;

(d) solid rods for tiebacks or tension members; and

(e) reinforcing bars for concrete.

(2) Aluminum. Aluminum, being a light metal in its high purity form, is soft and ductile but does not possess sufficient strength for structural applications. The addition of alloying elements imparts strength to the metal. Elements used as alloys in aluminum are copper, magnesium, zinc, silicon and small amounts of other elements such as chromium, usually with copper to obtain high strength structural shapes.

(3) Copper. Copper has several unique properties that make it a very useful materi' In addition to its high thermal and electrical conductivity it has h.gh corrosion resistance and can improve other elements by being readily alloyable. The most corrosion resistant of the copper alloys to seawater are aluminum brass, inhibited admiralty brass, and the copper-nickel alloys.

(4) Use in Coastal Structures. Steel is used as structural shapes in most types of coastal structure. It is used as well in composite structures, for example as rebar in concrete construction. Steel alloys have found many uses as bar stock, wire and wire fabric. Many alloys of aluminum, due to their high corrosion resistance as well as strength-to-weight ratios have also found many applications in marine structures. Copper, in addition to uses as pipe and sheathing, has a high alloying capability in bronze and brass that makes it a very useful element in the marine environment.

In the use of steel, alloys and other metals in the coastal environment, care must be taken to avoid direct contact of dissimilar metals that can form a galvanic couple. When dissimilar metals are in electrical contact with each other and immersed in an electrolyte, a potential difference is established; an electric current will flow and rapid corrosion will take place. If two dissimilar metals must be joined, then several precautions must be taken such as insulating the metals, avoiding unfavorable effects by keeping the cathode area small, placing a more anodic third metal in contact with the other two to provide sacrificial protection and investigating other possible solutions to protect the structure.

f. Wood.

(1) General. As a construction material, wood is available almost everywhere and at reasonable cost. It is a cellular organic material made up principally of cellulose, which comprises the structural units, and lignin, which cements the structural units together. A tree has distinct zones: bark, sapwood, heartwood, and the pith at the center. There is no consistent difference between the weight and strength properties of heartwood and sapwood. Because wood is produced by nature under various uncontrolled environmental conditions, such as geographical location, precipitation, exposure, and elevation, the product is highly variable. Also, trees are alive, producing wood of different properties at different ages. For a given characteristic or property of wood, such as its bending strength, both the mean value and its variation encountered about the mean should be considered.

Lumber grading rules are, in effect, specifications of quality. The size and number of knots, slope of grain and other strength reducing characteristics are judged and graded according to uniform standards so that working stresses can be assigned to specified quality.

Common construction species generally available in the United States are Douglas fir, southern pine, spruce, hemlock, redwood, cedar and other pine species such as lodgepole, ponderosa and white.

(2) Properties. The major mechanical properties of wood as they affect engineering design are:

(a) Tension Parallel to Grain. Tension parallel to grain creates a tendency to elongate wood fibers and cause them to slip by each other. Resistance to tension applied strictly parallel to the grain is wood's highest strength property, but if tension is applied at an angle to the grain or the cross section of the piece is reduced by knots or holes this strength may be materially reduced.

(b) Tension Perpendicular to Grain. Tension perpendicular to grain tends to separate the wood fibers along the grain and is the direction in which wood has the least strength.

(c) Compression Parallel to Grain. Compression parallel to grain creates a tendency to shorten the wood fibers in the lengthwise direction. Resistance of wood to this force is good but is affected by the angle of the load to grain and by the presence of knots and holes.

(d) Compression Perpendicular to Grain. Compression perpendicular to grain, such as the bearing under the ends of a beam or under a column, tends to compress the wood fibers together. The wood becomes more dense and the action may cause slight displacement at the bearing face.

(e) Shear Parallel to the Grain. The largest stress usually occurs along the neutral axis of a beam. During the drying of lumber, checks and splits may occur reducing the area in the plane of maximum shear; therefore the shear strength for design is reduced to accommodate this probability.

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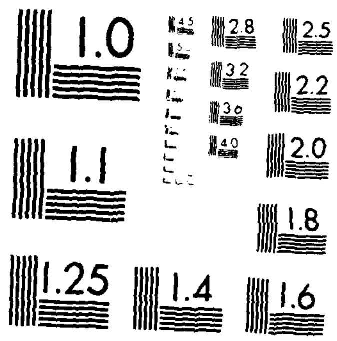

MICROCOPY RESOLUTION TEST CHART
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(f) Shear Perpendicular to Grain. Shear perpendicular to grain is not a design factor as effective control is applied through limits on design stress for shear parallel to grain.

(g) Fiber Stress in Bending. Fiber stress in bending creates compression in fibers on one side and tension in fibers on the other side of a beam. The higher stresses occur in the fibers most distant from the center. Deviations in the slope of grain and the presence of knots and holes in these outside faces reduces the resistance in the extreme fibers.

(3) Preservative Treatment. In order to extend the useful life of wood long enough to make it an economical and practical material for use in the coastal zone or other marine environments, it must be protected from its natural enemies, fungi, bacteria, insects and marine organisms. The most effective method of treating wood with preservatives is the pressure-treating process. The pressure-treating process requires placing the wood in an air-tight chamber in which either a vacuum or a pressure can be created while the preservative is introduced into the chamber. The preservative generally will penetrate the wood surface from 1.5 to 4 centimeters (0.5 to 1.5 inches) and coat the walls of the wood cells in this area. Penetration to 10 centimeters (4 inches) is required in some cases. Although two processes, the empty-cell and the full-cell process, have had success in preserving wood structures in marine environment, the full-cell process is most commonly accepted as the preferred treatment for coastal zone use.

Wood preservatives commonly used are grouped into two broad classes, preservative oils and waterborne preservatives. The preservative oils are considered the best wood protection in a marine environment and include byproducts of petroleum such as creosotes, coal-tar creosotes, and mixtures of these with other oils. They may include solutions of toxic chemicals such as pentachlorophenol or copper naphthenate. Waterborne preservatives include solutions of chromated zinc chloride, fluor-chrome-arsenate-phenol, chromated copper arsenate, and other toxic chemicals.

(4) Other Protective Methods. In a marine environment wood structures can be protected by other materials which are not strictly preservatives. Such protection is in the form of sheet metal, concrete jackets and flexible synthetic sheets such as vinyl and polyethelene films. Because virtually all organisms causing wood deterioration are aerobic, surrounding a wood element such as a pile with a jacket that prevents seawater containing free oxygen from coming in contact with the wood creates a hostile environment for the organisms.

(5) Durability. Wood, when properly treated with appropriate preservatives has a good history of satisfactory service in marine and coastal structures. Wood piles supporting piers and wharves, when not subjected to abrasion, have lasted many years. Wood sheet piles in groins, jetties, bulkheads and like structures will perform satisfactory. Care must be used in installing wood members to ensure that construction joints and connections do not damage the preservative protection or that field repairs are carefully and adequately made.

g. Plastics.

(1) General. Chemically the term "plastics" is applied to a large group of synthetic materials, including synthetic rubber, that are processed by molding or forming into final shape. Plastics that are soft and pliable at some stage in their production are formed into shape by the application of heat and pressure. They are organic compounds that are transformed into complex synthetic materials by chemical processes. They are high polymers in that they consist of monomer atoms joined together into molecular aggregations called polymers.

Plastics in general may be classified into two distinct groups, thermoplastics and thermosetting plastics. Thermoplastics soften repeatedly when heated and harden when cooled. Thermosetting plastics go through a soft stage only once. When hardened, an irreversible change takes place and they cannot be softened again. Plastics can also be combined for a particular end use, drawing together the best attributes of the blended components by copolymerziation. The products are called copolymers. During the production of plastics, additives such as plasticizers, fillers, colorants, stabilizers and impact modifiers can be added.

In addition to structural qualities, plastics are easily formable, corrosion resistant, lightweight, wear resistant, energy absorbant, impact resistant, flexible and ductile. A necessary consideration in the use of plastics is that plastics will burn, some easily, others slowly and others with great difficulty.

(2) Geotextiles. Plastics in the form of geotextiles have an important use in coastal structures, commonly functioning as filters in drainage, shore and embankment protection structures. Geotextiles are a relatively new material in the construction industry but have had a generally successful experience record as filters in selected coastal structures over the past 20 years. Substantial improvement in the design and materials selection specifications has also occurred.

The primary function of geotextiles when used as filters is to retain the protected soil (prevent piping) and remain permeable to water without significant head loss or the development of excessive hydrostatic pressure. To function satisfactorily, the geotextile filter must have physical durability and filtering integrity throughout the design life of the structure. In the selection of a geotextile for a filter, the chosen fabric, in addition to having required physical and chemical properties, should be of a kind and finished form consistent with the site-specific requirements.

Fabric construction is a predominant factor affecting performance. Woven fabrics are commonly manufactured by crossing the yarns at right angles, overlapping one over the other, the yarns being monofilament, multifilament, mono-multifament or slit-film. Nonwoven fabrics include all materials not woven or knitted. They consist of discrete fibers, which may be random or pattern oriented in the fabric. The bonding methods described are needle punched, heat bonded, resin bonded, and combination bonded. Combination fabrics are produced by combining woven and nonwoven fabrics by one or more bonding methods.

(3) Use in Coastal Structures. Because geotextiles are relatively new as a construction material, there has not been sufficient time to develop agreed upon standard testing techniques for the most important characteristics a fabric should have for specific applications. However, they are finding many uses in coastal structures. Different fabric specifications may be required for specific uses, such as replacement of stone filters under riprap, drainage control by silt retention fabrics, and road stabilization by road or highway fabrics. Fabric users should seek the advice and recommendations of knowledgeable sources with experience in the specific use being considered, such as consultants and more than one manufacturer.

Many forms of plastics other than geotextiles are also used in coastal structures. Flexible plastics are used as mold forms for concrete and for wrapping timber pile to provide protection from marine animals and for wrapping metal piles to prevent corrosion. Molded forms have applications as rubbing strips, fenders and bumpers. Plastic extrusions in the form of pipe and culverts are in common use. Pipe may be reinforced or not depending on the structural strength required.

h. Recycled and Other Materials. Generally recycled materials consist of a variety of materials that may be available in a given location and are normally used in emergency situations as temporary (occasionally as permanent) protective devices against damaging waves or currents. Such materials should have a specific gravity greater than 1.5 to be useful unless a floating type of structure is needed.

Materials considered in this category are salvaged concrete, concrete rubble, crushed concrete, recycled asphalt used either as rubble or crushed, blocks and bricks, and salvaged steel structures. Normally, because of the emergency type use of recycled materials, little consideration is given to the properties of such materials other than their specific gravity. Also, little concern is given to their environmental impacts; however, these impacts would generally be different than for the materials before recycling or reuse.

Recycled or salvaged materials have been used for many years for emergency repairs or to construct temporary structures. In many cases these temporary structures have remained in place for many years.

Salvaged concrete, either as rubble, crushed or unbroken has been used to repair revetments, groins, jetties and breakwaters. These materials may not have a pleasing esthetic appearance, especially if they contain reinforcing steel. If located in a recreation area, the reinforcing steel may create a safety hazard. Of course, exposed reinforcing bars will corrode at a rapid rate causing accelerated concrete spalling and deterioration. Generally these materials are used as a substitute for stone in coastal structures.

Recycled asphalt can be used as an underlayer in coastal structures. Although it is relatively hard and unflexible because of its age, it will retain its broken shape for extended periods of time and further deterioration is not a problem. Recovered asphalt may be crushed and used as core or bedding material in coastal structures, but unless well graded, it does not make a satisfactory filter material. Crushed asphalt is also finding greater use as a base material for highways, roads, streets, and parking lots.

Bricks, hollow concrete blocks, and cinder blocks have been used as temporary repair materials; however, they generally break down during handling and are not of much long-term value. Also they have no value as an underlayer or armor layer.

Salvaged ships and barges have been used as temporary breakwaters by manuevering them into a selected location, sinking them and then filling them with rock or gravel to provide stability. Removing these devices when a permanent structure is desired or upon their disintegration, is usually a difficult problem. Other salvaged materials such as railroad cars and automobile bodies have been used in bank or shore protection, however, they are not satisfactory and are usually unsightly and hazardous if located where people may visit. Used rubber tires have a variety of uses such as fenders on barges, work boats and docks. They have also been successful as floating breakwaters to protect basins against short-period waves. Several different arrangements have been model tested. Flotation has been created by filling tires with urethane foam. If anchored in place or on the bottom, tires have served as a revetment and to slow the bed movement of littoral drift.

i. Protective Systems.

(1) General. Protective systems are applicable to steel and alloys; wood, and concrete, usually for esthetic reasons or, in some few cases, to decrease water penetration into relatively porous concrete. Protective systems are classified in two categories; coating and cathodic protection. Each of these systems may be used separately, but in many instances cathodic protection can be successfully used to supplement coating systems.

(2) Coatings. Protective coatings range from mere decorative paints to complex and multicoat systems requiring careful surface preparation, proper coating application techniques, and the careful selection of coating systems. In the consideration of a coating requirement, the first step is to consider the type and kind of surface to be protected, i.e., wood, concrete, steel or other metals and alloys. Next consider the environment the structure surface is exposed to, such as a marine atmosphere, a tide or splash zone or a submerged zone in either fresh or salt water. With this information and other specific data as set forth in Section XI, the coastal engineer may then consider the generic category as well as the specific type of coating within a category that is best suited for the protection of a given structure.

The types of coatings and their generic classifications are discussed in Section XI. To adequately evaluate a coating's protection performance it is necessary to consider the properties of the coating material, the surface preparation requirements, and the application procedure as well as the drying or curing processes. To aid evaluation, Section XI discusses the surface preparation processes including resulting metal surface anchor patterns, the number of coats and thickness, and the drying or curing processes necessary to obtain a good coating system that can be expected to properly protect a structure. Coatings are applied by brush, roller, spray (both air and airless), and dipping.

Coating repair is a common procedure; however, there are precautions that must be taken to ensure successful repair. Coating compatibility is a must

to provide good bonding of the repair coating or to prevent any of the normal types of coating failures. Coating failures may be identified by the presence of blistering, undercutting, surfacing cracking, delamination, alligatoring, or chalking. Coating must have strength, adhesion, resistance to the environment and, many times, a pleasing appearance to properly function.

(3) Cathodic Protection. Cathodic protection is an electrical process to protect metal structures in an electrolyte. The electrolyte may vary from seawater to freshwater, saturated soil and even relatively dry soils. Disolved ions of acids or alkali salts tend to promote metal deterioration which can occur in localized areas or over large general areas of a metal surface. Metal corrosion is a natural process involving electrochemical reactions with a resulting flow of direct current from the anodic areas (the corroding areas) to the cathodic areas of the structure through the surrounding electrolyte due to the electrical potential difference between the two types of areas. Cathodic protection is the process of inducing an outside electric current in the opposite direction and in this manner stopping the normal corrosion process.

The design and installation of a cathodic protection system is highly technical. To ensure design of an effectively operating system, field conditions of the structure must be examined to determine the total amount of electrical current required to cathodically protect the structure and to ensure proper current distribution. It must also be determined that there will be no interference with other structures in the vicinity and that potential differences within either the protected structure or of adjacent structures are not impacted to ensure that no cathodic protection interference conditions exist. Cathodic protection requires periodic maintenance and inspection to keep it in good working order.

Generally good protective systems, both coatings and cathodic protection, are economical, require maintenance, and will substantially extend the service life of well-constructed structures.

3. Some Present Investigations of Coastal Construction Materials.

a. Stone. Stone is one of the most widely used materials in coastal structures and shore protection works. There are two basic areas of research on stone: the uses of stone in shore protection structures and the characteristics of stone for use in coastal structures.

Stone is used in revetments, jetties, groins, bulkheads, seawalls, and other miscellaneous types of structures. Studies are being done on new types of shore protection structures such as semisubmerged offshore structures, on new structure configurations for jetties, on different distributions or arrays of stone in armor units or layers, on the reliability of breakwater model tests, and on the effect of breakwaters on waves. Programs have been initiated to monitor and evaluate the performance of existing coastal structures in terms of their effectiveness, maintenance cost and life. This area of research also deals with development of field techniques and criteria for the functional and structural design of coastal structures. Work is also continuing on the evaluation of parameters used for determining the effective

elevation of structures, the slopes of revetments to reduce runup, and the size of armor stone to dissipate energy.

The use of stone in coastal structures is based primarily on experience. Continued research is needed on the development of testing procedures, criteria, and methods of quarrying to determine and produce rock characteristics that are desirable and suitable for use in coastal structures. Current research includes various tests for shrink and swell behavior, wetting and drying effects, mineralogic composition, specific gravity, and other physical and chemical properties.

b. Earth. Current investigations and studies relating to the use of earth materials in the coastal and marine environment deal primarily with the behavior of soils under various nearshore conditions and their use in connection with coastal structures. These investigations include numerous programs that are in progress to develop field techniques and criteria for use in design, construction, and maintenance of effective beach and dune protection. The programs seek to describe and predict the interactions between the materials that make up the coasts and the forces that act upon them. Studies include the development of mathematical models that designers can use to determine how much sandfill is required to adequately protect a segment of shore for a certain timespan and how often additional fill will be required. Studies are in progress to determine the effective use of earth materials in low-cost shore protection. New dredge disposal techniques are being studied to aid in beach nourishment projects and sand bypassing across coastal inlets. Several field research facilities and projects have been established to study coastal processes and their long-term effects on the erosion of and protection of the natural coastline materials.

Research is also continuing on the engineering properties of the various soils. These studies include the determination of density and porosity of sea floor sediments, the grain-size distribution of beach materials, and the shear strength and consolidation characteristics of estuarine deposits.

c. Portland Cement Concrete. Concrete structures are being increasingly utilized for a wide variety of applications in the marine environment. Structures are becoming more sophisticated and are being located in areas of more severe exposure (e.g., ice and open sea), and subjected to cyclic and impact loads. Consequently, their performance requirements become increasingly severe and critical. Investigations are being performed relating to internal response of structural elements, environmental conditions in which the structure must serve, new materials and configurations, construction practices and repairs, and new uses in the ocean.

Existing problems relating to concrete design include cracking, spalling, and corrosion of reinforcing steel, as well as the purposeful overdesign and over-reinforcement of structures in an effort to cover the range of uncertainty. These problems indicate the need for additional investigation to better understand the properties of concrete. Investigations include:

(1) Corrosion of reinforcement in submerged structures with varying widths of cracks. Also where cracks are repeatedly opened and closed under a large number of cycles there appear to be an

accelerated degradation which may be due to hydraulic fracturing of the concrete by entrapped water.

(2) Placement of mass underwater concrete is being tested. Tremie concrete mixes and placement procedures are being investigated at the University of California and mass concrete placement in the deep ocean is being tested by U.S. Naval Civil Engineering Laboratory at Hueneme. Also, investigation of thixotropic admixtures to prevent segregation of concrete when flowing through water is being considered.

(3) Failure of dolos units and other armor units indicates the need for additional investigation to find more stable shapes, or the possible need for reinforcement to tie the member internally and improve its flexural strength. Repairs to precast concrete units of this kind, as well as other concrete structures have been carried out using epoxy injection. Continued tests on repaired units are needed to determine fatigue and ultimate strength as well as to gain a better understanding of the impact on other properties of concrete.

d. Other Types of Concrete and Grout.

(1) Bituminous Concrete. Asphalt is made from crude oil and refineries in recent years are using crude from many different sources, making the characteristics of presently produced asphalts different from those previously produced. This results in problems in the handling and placing of asphalt cement and in its performance. Asphalt-related problems generally divide into two categories: workability problems and performance problems. Workability problems, which make asphalt more difficult to mix and place, seem to be common. They result from mixing the different crude sources.

Some evidence indicates that equipment changes, such as using drum plant mixing in which the aggregate and asphalt are added to a drum simultaneously, can result in a softer asphalt with a higher moisture content. The introduction of vibratory compactors, which densify by dynamic energy, requires a different compaction process than steel tandem rollers.

There are many variables that can affect an asphalt: cement, fines, aggregate, temperature of mix and roll, etc. More research is needed to identify and clarify the role of variables. More investigation of the compaction process is necessary.

(2) Preplaced Aggregate Concrete and Portland Cement Grout. This is essentially a special application of Portland cement concrete; therefore, the investigations relating to Portland cement can also result in better use of this type of concrete. By investigating the performance of past, present, and future projects using preplaced aggregate and Portland cement grout, improved techniques and other applications should be found.

(3) Soil Cement. Soil cement is also a special use of Portland cement and additional investigation can create an understanding of how to use local soils, especially the very fine and clay type soils, successfully.

(4) Sulfur Cement Concrete and Grout. With the increased production of sulfur, as a result of refining more sour crude, larger quantities of sulfur become available. This makes sulfur cement concrete and grout more economically competitive for many special uses. Ongoing research and testing is aimed at improving sulfur-asphalt materials by developing additives to improve physical properties, such as those that allow mixing at temperatures above 160° Celsius to prevent dehydrogenation. In sulfur concrete development, the discovery of other plasticizers to improve its physical properties and upgrade its heat resistance is an important activity.

e. Structural and Other Metals.

(1) Steel. Much of the effort in the research and development of steel and steel products for coastal construction is devoted to the metallurgy in steelmaking, in order to develop products that are more corrosion resistant when exposed to the marine environment. Progress has been made with recent development of ASTM grades A242 and A588, using small amounts of vanadium, zirconium, columbium and titanium. These alloys exhibit improved strength and yield values. However, the cost of these products is high and, with the improved protective systems available (both coatings and cathodic protection), very little of these steel alloys is produced. Studies in the application and control of cathodic protection are ongoing to improve the understanding of hydrogen embrittlement and stress corrosion cracking of metals, that may lead to greater use of structural steel in future coastal structures.

(2) Aluminum and Copper. The studies and investigations of aluminum and copper, as well as other metals, are similar to those of steel. Much of the research work is concerned with a better understanding of the physical-chemistry of the oxide films that are responsible for the passivity and corrosion resistance of these metals. These studies may lead to new alloys and resulting allotropic modifications that might improve corrosion resistance as well as enhance some physical properties of the metals, including resistance to halogen and acidic ions.

There is so much research in progress that it is difficult to estimate at this time what new knowledge may contribute to the improved use of metals in a marine environment.

f. Wood. Because wood is produced by nature under various uncontrolled environmental conditions, the product is highly variable. Also, the fact that the tree is alive and produces wood of different properties at different ages complicates the analysis of properties of wood. Recent investigations on the strength properties to determine the material variability of clear wood are based on the statistical probability of sampling.

(1) Elastic Parameters. Present design often involves curved members and three dimensional stress distributions. Therefore, recent emphasis has been directed toward the determination of strength and elastic characteristics of wood in all the principal directions. Prediction equations have been developed recently which allow the estimation of all the elastic parameter values of wood (Bodig and Goodman, 1973). Also, there is considerable interest in predicting the elastic and strength characteristics of wood at any arbitrary ring and grain angle.

The determination of the elastic parameter values is based on the linear part of the stress-strain curve. For ultimate stress design, the knowledge of the nonlinear part of the stress-strain curve is very important. Investigation is also being done on the stress interaction behavior of wood.

One of the problems associated with the theoretical prediction of the strength of wood is the lack of understanding of its mechanism of failure. Fracture mechanics of wood as well as the concept of energy of distortion limitation, are also being investigated.

(2) Time-Dependent Characteristics. Because of the time-dependent stress-strain behavior of wood a large amount of investigation has been concerned with the rheological properties of this material. Nonlinear time-dependent relationships, cyclic loads, and cyclic environmental factors all complicate these relationships. Among the various rheological properties, creep behavior appears to be the property most often needed in designing with wood. The effect of duration of load on the strength properties also is being investigated. Dynamic forces act for a very short duration and under these conditions wood appears to be stronger and stiffer than under static loading.

(3) Wood Composites. When compared to other construction materials, wood is one of the most efficient materials available on a pound per pound basis in stiffness and strength along the grain. However, its efficiency is much lower if across-the-grain direction is considered. Thus for specific engineering purposes it is necessary to rearrange the wood in relation to its natural form. This necessitates the manufacture of composites such as laminated beams, plywood, particleboard, hardboard, and fiberboard. Further modifications can be made by high density overlays and impregnations and preservatives.

Some investigation and testing of laminated wood utilizes a proof-loading concept to establish the laminating combinations and their associated design stress. The research is intended to determine what tensile proof load should be used in order to justify strength levels and what percentage of the tension zone laminations should be subject to the proof load level. In order to utilize more flexibility in laminating combinations, a project is in progress which will provide criteria for combining different species.

g. Plastics. The number of plastic materials and resins available today is so great and the variety of synthetics available in each family of plastic resins is so large that it is virtually impossible to identify significant investigation and research that is ongoing and of importance to coastal engineering materials development. Investigations and development occur in three general areas: processing and machinery, new resins, and resin modifications by additives.

(1) Processing and Machinery. The development of new resins will not lead to an improved product until the machinery for processing such resins or modified resins can be developed. The new machinery will control the plastic manufacturing in a manner to properly produce a given product with the required physical properties.

Molding machines have been developed to mold liquid polymers and technology is now being offered for injection molding of ultrahigh molecular weight polyethylenes. Systems for extruding polypropylene using water cooling of the bubble to obtain good toughness and high clarity are being developed. A new development in injection molding is making a solid skin of one type of plastic and a foamed core of another. The manner in which plastics are made impacts on the physical properties of a material such as impact resistance, flexural strength, and heat distortion, permitting these properties to be substantially improved with improved processing capability. The improvement of physical properties will provide for a longer service life of the present use of both rigid and flexible plastics. As flexural strength, resistance to impact and heat distortion are increased, plastics may find an increasing use as structural members.

(2) New Resins. Polyester resins form a large family of resins. In the manufacture of resins, three basic controls (i.e., density or degree of crystallinity, molecular weight, and molecular weight distribution), result in a great variety of resins. The abundance of glycols and dibasic acids developed from petroleum intermediates provides a wide latitude in designing polyester resins to meet specific requirements. Unsaturated polyesters can compete with epoxies, phenolics, and other plastics in electrical, physical and mechanical properties. These resins predominate in applications requiring corrosion resistance. For example, nonair-inhibited types are used as a material in boat hulls, bouys, and decks, and for coating wood, concrete, metals, and other structures. High temperature resistant resins such as linear aromatic polyesters represent another new development. This particular polymer also has a high resistance against most organic solvents.

Polyethylene has a very simple molecular structure, but it is capable of almost infinite variation and modification. The most recent development has been in the very high density polyethylene resins that result in a hard crystalline character. These developments may result in improved properties such as impact resistance, tensile strength, and abrasion resistance for use in bouys, fenders and bumpers, and unreinforced pipe.

(3) Resin Modifications by Additives. Virtually all resins will have different properties due to the incorporation of additives. Antioxidants are used to prevent degradation of resins at high temperature. Ultraviolet stabilizers prevent deterioration in atmospheric exposures. Fillers are used for their reinforcing properties, such as the use of chopped glass fibers to increase strength and stiffness. Air may be considered a filler when injected into a resin during processing to produce a cellular or foamed plastic.

Dispersion resins are fine particle resins which can be dispersed in plasticizers to produce liquid systems that are essentially 100 percent solids. These systems are used in the manufacture of protective coating and paint systems. Many of these systems are used to coat, impregnate or saturate fabrics and yarns as well as to coat paper, and leather.

New developments in the use of plastics in coastal structures will be continuous for many years to come since a large variety of plastic resins are available, their molecular structure can be rearranged to form new plastics,

and the physical properties of the new plastics can be changed and improved through the manufacturing process and the addition of additives and plasticizers.

(4) Geotextile Filters. The development, investigation and testing of fabrics is fragmented and there are many activities overlapping in effort. The manufacture of filter fabric is changing in some instances due to the ongoing development of nonwoven fabrics with controllable thickness, elongation, and filtration capabilities. Methods are being investigated to characterize fabric as to the size and shape of openings and the details of clogging of the fabric. Tear propogation in fabrics is being studied. Mechanical property analysis to indicate the amount of deformation that a fabric will undergo is being performed. Information about anchoring to indicate the required friction between the fabric and the soil is also being investigated. Filtration mechanisms (and particularly the soil structure arrangement resulting from the waterflow), flow rate, permeability, and piping are being evaluated and laboratory test methods are being recommended. The results of these investigations and others that will come along in the future will provide data for expanded and better use of fabrics.

h. Protective Systems.

(1) Coatings. One of the principal means of preventing deterioration of structures is through the use of protective coatings. Coatings may be specified on a formulation basis, on a performance basis, or by a combination of the two. The formulation-type specification does not take advantage of the manufacturer's experience and formulating knowledge, the responsibility for obtaining a suitable coating being the specification writer's and his technical sources. The principal alleged merit of a performance-type coating is that it does take advantage of the manufacturer's knowledge and experience and may be a real advantage if the manufacturer is highly experienced in formulating coatings for the particular contemplated usage. A principal difficulty with performance-type specifications is that acceptance tests, which purport to show that a coating is satisfactory for a specific use, must necessarily be finished in a short time and frequently have little significance in predicting actual performance. Performance tests include flexibility, hiding power, immersion resistance, gloss, resistance to weather or salt spray tests.

The development of improved coating systems involves three areas of investigation and testing: surface preparation, coating application techniques and improved materials. In many situations environmental constraints have required innovations and improvements in all three areas of coating systems development.

(a) Surface Preparation. Surface preparation is accomplished in many ways: solvent cleaning, hand and power-tool cleaning (wire brushing), pickling, flame cleaning and blast cleaning (sandblasting).

Good coating performance requires good adhesion to the structure surface. Preparing the surface for coating application is critical. In solvent cleaning, mineral spirits are frequently used but must be sufficiently refined as to not leave oily residues upon evaporation. Solvents that leave

no residue on a surface to impede the bond of coating require additional investigation. However, study in this area is limited as solvent cleaning is usually used with other surface preparation processes.

Hand and power-tool cleaning of metal surfaces is widely used; however, this process usually produces some areas of polished metal, which are not conductible to good coating adhesion. Developmental studies are being done in an effort to devise means of removing loose contaminating particles from a structure surface by designing wire tips for brushes that will remove contaminants and improve brush wear.

In pickling, acids such as sulfuric, hydrochloric, phosphoric and nitric are used. Inhibitors are added to minimize metal loss. However, acids leave considerable residue on metal surfaces that can cause coating adhesion problems. The elimination of residues by hot-water rinsing helps but redeposited salts or absorption of atomic hydrogen may cause metal embrittlement. Means to prevent these possibilities must be considered.

Flame cleaning removes only loose rust particles and grease, therefore it must be followed by wire brushing and coating application while the surface is dry but cool. Because this process has a high cost, it is not used to a great extent and little improvement in its use is being studied.

Blast cleaning is the most effective method of cleaning metal surfaces. The degree of blast cleaning can be determined by type of blasting material, the pressure used in blasting,and the amount of time of blasting per unit area. The metal surface anchor pattern developed as a result of blast cleaning can be controlled. Certain coating systems may require a deep anchor pattern, others a shallow anchor pattern. Some blasting materials produce a rounded anchor pattern while others a sharp pattern. Because different types of coating primers require different adhesion conditions, surface preparation must be considered as a part of the coating system.

(b) Coating Application Techniques. Coating application techniques are an integral part of a protective coating system. As new and better coating systems are developed,new application systems must also be created. Application systems presently in use are brush, roller, various spray methods, flow and electrostatic processes. The electrostatic processes came about with the development of plastic resins which are applied in the dry powder form. This application system involves a specific surface preparation process. Still in the development and improvement stage is an improvement in the process that will produce a required thickness of a near perfect coating, without pinholes or holidays, using a variety of plastic resins. Present electrostatic applications are very good but the adaptability of this procedure to a wider variety of resins or the development of a greater number of coating resins for use in this process must continue.

(c) Improved Coating Materials. Asphalt coatings consisting of a dispersion of high molecular weight hydrocarbon compounds (asphaltenes) in heavy residual oils are made into asphalt enamels,hot applied, solvent-reduced asphalt coatings and emulsions. Because the asphalt residue, from which the coatings are made, is used as a raw material for many other products, the cost of such coatings is rising and there is relatively little asphalt coating research and development activity.

Coal-tar pitch, the residue from distilled coal tar, is used to manufacture coal-tar coatings by cutting back the pitch with coal-tar solvents and usually adding mineral filler (extender pigments) such as magnesium silicate. Most recent developments of the use of coal tar in coating systems is in the coal-tar epoxy systems. These systems contain epoxy resins, pigments, solvents, curing agents, coal-tar pitch and gelling agents. The broader use of coal-tar pitch with a greater variety of resins is continually under development at present. The development of plastic resins for use in new coating formulations is part of the research and development activities discussed in Section IX, Plastics.

(2) Cathodic Protection. Maximizing the efficiency of corrosion control requires a thorough understanding of the environment and its variability to which structural materials are exposed. This is particularly true of metals. However, environmental considerations are also important in considering the durability of all construction materials.

(a) Environmental Variability. Optimizing cathodic protection systems in the marine environment requires a detailed knowledge of the seasonal variability of dissolved oxygen, temperature, and the saturation rate of the water with respect to carbonates. Although complete protection can and is being achieved on many structures without any prior knowledge of these variables, the design of the most economical system utilizing a combination of impressed current, sacrificial anodes, and coatings is not possible without detailed knowledge of the environmental conditions.

The four variables important to corrosion for which there exists a large enough data base to permit general surface water mapping of the oceans are temperature, salinity, dissolved oxygen, and pH. Other variables may also be of importance but enough data are not yet available to significantly evaluate their impact on a global scale.

Premature anode material failures as a result of variation in environmental conditions are being examined in more detail. Attention is being given to electrochemical reactions and conditions at the anode-environment interface when chloride and sulfate ions are discharged in the anodic process, affecting the anode material.

(b) Buried and Embedded Steel. Although some ten cathodic protection criteria for buried steel structures have been used throughout the world, a universally acceptable criterion is still not available. Frequently different criteria give conflicting evaluations of the state of protection. This situation has been due primarily to the lack of suitable electrochemical procedures to monitor and evaluate the actual state of protection at the structure-soil interface. A great deal of investigation of this problem, both in the field and laboratory, is being done and reported regularly in the literature.

Some studies indicate that the current density for cathodic protection of embedded steel in concrete is controlled primarily by the rate of oxygen diffusion through the concrete. Measurements indicate that the resistance to oxygen diffusion may be ten times higher through the interface between cement paste and steel than through the concrete cover.

Studies to provide a better understanding of the electrochemical and the electrode kinetics reactions at the surface of the metal-environment interface and to improve field measurement techniques are ongoing in many places in the world. This information will provide engineers with a means of determining better and more efficient cathodic protection designs required in any local conditions in the future.

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APPENDIX A

SPECIFICATIONS AND APPLICATIONS FOR STEEL SUITABLE FOR MARINE SERVICE.

ASTM designation	Title of standard	Application
A36-77	Standard Specification for structural steel	Bridges, bulkheads, general structures
A131-78	Standard Specification for structural steel for ships	Ship construction, tanks (shapes, plates, rivets)
A242-79	Standard Specification for high-strength, low-alloy structural steel	
A252	Standard Specification for welded and seamless steel pipe piles	Structures, form for cast in place concrete piles
A283-79	Standard Specification for low and intermediate tensile strength carbon steel plates, shapes, and bars	General structure, tanks
A284-77	Standard Specification for low and intermediate tensile strength carbon-silicon steelplates for machine parts and general construction	Machine parts, general construction
A328-75a	Standard Specification for steel sheet piling	Sheet piling, dock walls, and cofferdams
A440-77	Standard Specification for high strength, structural steel	Bridges
A441-79	Standard Specification for high-strength low-alloy structural manganese vanadium steel	Bridges, buildings; weight savings and added durability
A514-77	Standard Specification for high yield-strength, quenched and tempered alloy steel plate, suitable for welding	Welded bridges and other structures

A529-75	Standard Specification for 42,000 psi (290 MPa) minimum yield point {1/2-in (12.7 mm) maximum thickness}	Buildings
A572-79	Standard Specification for high-strength low-alloy columbium-vanadium steels of structural quality	Bridges, building structures
A573	Standard Specification for structural carbon steel plates of improved toughness	Steel plates and sheet piling
A588-80a	Standard Specification for high-strength low-alloy structural steel with 50,000 psi minimum yield point to 4-in thickness	Bridges, buildings; weight savings and added durability
A633-79a	Standard Specification for normalized high-strength low-alloy structural steel	Serves at -45^{o}C and higher
A690-77	Standard Specification for high-strength, low-alloy steel H-piles and sheet piling for use in marine environments	Dock walls, seawalls, bulkheads; providing 2 to 3 times greater resistance to seawater splash zone than ordinary CS
A699-77	Standard Specification for low-carbon manganese-molybdenum - columbium alloy steel plates, shapes, and bars	General application; grades 3 and 4 suitable for temperature down to -45^{o}C
A709-80	Standard Specification for structural steel for bridges	Carbon and high strength low alloy steel plates and sheets
A710-79	Standard Specification for low-carbon age-hardening nickel - copper - chromium - molybdenum-columbium and nickel-copper-columbian alloy steels	Plates, shapes and bars for general application

APPENDIX B

MECHANICAL PROPERTIES OF ROUND WOOD PILES

TREATED WITH PRESERVATIVES FOR USE IN SALTWATER

1. Source of Information

The Civil Engineering Laboratory at the Naval Construction Battalion Center, Port Hueneme, California, investigated the effects of various commercial preservative treatments on the mechanical properties of wood. The investigation and results are described below in excerpts from Eaton, Drelicharz and Roe (1978).

2. Preservative Treatments

"Thirty-five peeled Douglas fir logs as nearly alike as feasible were selected from on-hand supplies and cut into pieces approximately 30 feet long, nominally 12 inches in diameter at the butt end and 7 inches in diameter at the tip end. These were separated into seven lots of five piles each. The seven different lot treatments were:

(a) Untreated,

(b) standard creosote treatment,

(c) ACA, 2.5 lb/cu ft of sapwood,

(d) ACA, 1 lb/cu ft of sapwood, followed by kiln drying, followed by standard creosote treatment,

(e) ACA, 1 lb/cu ft of sapwood, followed by air drying, followed by standard creosote treatment,

(f) CCA, 1 lb/cu ft of sapwood, followed by kiln drying, followed by standard creosote treatment, and

(g) CCA, 1 lb/cu ft of sapwood, followed by air drying, followed by standard creosote treatment.

All preservative retentions met the minimum American Wood Preservers' Association requirements except for the dual-treated CCA + creosote, both air- and kiln-dried (see Table 1)."

"Forty peeled southern pine logs as nearly alike as feasible were selected from on-hand supplies and cut into forty pieces approximately 30 feet long, 12 inches in diameter at the butt end, and 7 inches in diameter at the tip end. These were separated into eight lots of five piles each. Seven lots were given the same levels of treatment as the seven lots of fir. An eighth treatment - 2.5 lb of CCA/cu ft of sapwood - was used on the remaining eighth lot. All preservative retentions met the minimum American Wood Preservers' Association requirements."

Note that the retentions for some preservatives were well above the specified minimums.

Table B-1. Preservative retention of marine piles within a 1-inch depth.

Treatment[1,2]	Specific Gravity	Average Preservative Retention of Five Piles per Treatment pcf				
		Creosote	Total Metallic Salts	Chromium	Copper	Arsenic
Southern Pine						
Untreated	0.54	0	0	0	0	0
Creosote	0.54	28.9	0	0	0	0
2.5 ACA	0.54	0	6.76	0	3.43	3.33
1.0 ACA, kiln, creosote	0.53	29.8	2.04	0	1.05	0.99
1.0 ACA, air, creosote	0.55	29.5	1.70	0	0.81	0.89
1.0 CCA, kiln, creosote	0.54	27.6	1.58	0.68	0.23	0.67
1.0 CCA, air, creosote	0.55	31.1	1.39	0.63	0.18	0.57
2.5 CCA	0.56	0	5.18	2.46	0.83	1.89
Douglas Fir						
Untreated	0.47	0	0	0	0	0
Creosote	0.44	21.6	0	0	0	0
2.5 ACA	0.44	0	4.67	0	2.37	2.30
1.0 ACA, kiln, creosote	0.46	30.6	1.12	0	0.53	0.59
1.0 ACA, air, creosote	0.46	30.5	1.05	0	0.51	0.54
1.0 CCA, kiln, creosote	0.44	18.7	0.79	0.36	0.12	0.31
1.0 CCA, air, creosote	0.46	16.1	0.55	0.27	0.07	0.22

[1]ACA - ammoniacal copper arsenate
CCA - chromated copper arsenate

[2]Number represents pounds of chemical per cubic foot of sapwood.

3. Bending Tests of Full-Sized Piles

"The 75 piles were then destructively tested at the Forest Research Laboratory, Corvallis, Ore., in a random chronological manner."

"Piles were selected randomly for testing. They were loaded into a 600,000-lb capacity, universal testing machine from the Civil Engineering Department of Oregon State university. If a pile was curved, it was rotated

before the loading procedure until there was no horizontal curve. The loading heads were loaded until they almost touched the pile, load and deflection recording devices were zeroed, and circumferences were measured at the tip, middle, and butt of each pile. Moisture contents of untreated or creosote-treated piles were measured with a resistance-type moisture meter near a loading head at a depth of 0.5, 1, 1.5, 2, and 2.5 inches."

"Data were recorded in two ways: (1) by means of a strip chart attached to the universal testing machine and written data sheets, and (2) a magnetic tape, digital recorder and microphone provided by CEL. The tape reel number, tape footage, date, time and specimen numbers were recorded on the data sheet, and the tape recorder was set for recording. The specimen number, date, and weather report were spoken into the microphone, and some sounds were recorded of the breaking piles. The loading rate was 0.53-in./min until failure when the head speed was increased until 10 inches of deflection occurred. Maximum breaking load (P_{max}) was recorded on the data sheets as were abnormallities such as severe slope of grain or overabnudance of knots, and the type of failure (i.e., compression, tension, or shear)."

"After these bending tests, a 4-ft-long butt specimen and a 3-in.-long cross section near the failure were cut from each pile. The 4-ft-long specimens were sent to CEL and the 3-in.-long sections were saved for preservative analyses. Moisture content specimens were taken near the point of failure. Salt-treated and untreated specimens were oven-dried. The Karl Fischer method was used to determine moisture contents of creosote and salt-treated specimens. Sections of piles from the vicinity of failure points were cut and saved."

4. Compression Tests on Piles Segments

"The 4-foot butt specimens obtained earlier were squared off with a table chainsaw to a length of 45 inches. The specimens were submerged in water in a retort and 90 psi of pressure applied to bring the wood to its fiber saturation point. This water-impregnation treatment required 1 day for pine and 1 week for Douglas fir. Moisture contents of creosoted specimens were recorded with five readings at 1/2-inch-depth increments up to a total depth of 2-1/2 inches in the middle of a piece 2 feet from its end. The moisture content of dual-treated piles was assumed to be similar to creosote-treated material. The moisture content of salt-treated piles was assumed to be similar to the untreated specimens. The average moisture contents after pressure treatment with water were 30% for southern pine and 28% for Douglas fir."

"The length and circumference at butt and tip of each specimen was measured. Loading to failure was at the rate of 200 kips/min. The location of each failure was recorded."

5. Results

"Table 2 shows the data obtained from this program. Table values are based on a limited number of piles, selected originally for high quality appearance and apparent low variation from pile to pile. Thus, the table values may be higher than they would be if unselected run-of-the-mill piles were used. As can be seen, there was a definite decrease in the mechanical properties of the wood with treatments, some as high as 55%."

Table B-2. Average mechanical properties of piles.

Type of Treatment	No. of Test Piles	Flexural Properties: Modulus of Rupture MPa	Flexural Properties: Modulus of Elasticity in Flexure GPa	Flexural Properties: Average Absorbed Energy in Flexure kJ/m^3	Compressive Strength, F_c MPa
Fir					
Untreated	5	57.87	13.25	43.70	23.07
Creosote	5	47.31	10.92	28.97	----[1]
ACA dual[2]	10	42.13	10.60	21.09	18.71
CCA dual[2]	10	26.50	8.074	23.19	16.09
ACA	5	38.75	9.763	14.33	16.97
Pine					
Untreated	5	55.21	13.39	36.13	----[1]
Creosote	5	41.02	----[1]	----[1]	----
ACA dual[2]	10	32.58	10.81	19.51	----
CCA dual[2]	10	28.73	9.935	16.64	----
ACA	5	38.16	10.60	----[1]	---
CCA	5	37.30	-----[1]	----[1]	----

[1]No value is provided because of the large spread in measured values for a small number of samples.

[2]Includes both air-dried and kiln-dried specimens (5 each).

"Table 2 may be useful to the designer and planner. Data on strength of piles found in handbooks usually refer to untreated piles. A designer can obtain from Table 2 a rough estimate of the ratio of strength for his choice of species and treatment compared to that of the stronger untreated piles. Then the number of piles required for the job can be estimated."

6. <u>Conclusions</u>

"For Douglas fir piles, it is concluded that:

(a) Dual treatment (ACA and creosote or CCA and creosote) or treatment with only ACA will reduce some mechanical properties of a pile more than treatment with creosote. For specific numerical reduction refer to Table 2.

(b) Of the two dual treatments, CCA and creosote reduces some mechanical properties of a pile more than ACA and creosote (refer to Table 2.

(c) In dual treatments, kiln drying is more deleterious than air drying."

"For southern pine piles, it is concluded that:

Dual treatment (ACA and creosote or CCA and creosote) or treatment with ACA only are more deleterious to more mechanical properties than treatment with creosote (refer to Table 2)."

7. Recommendations

"It is recommended that:

(a) In areas where piles are destroyed mainly by mechanical means, creosote-treated piles should be considered.

(b) In areas where piles are destroyed mainly by biological attack and it is known that dual-treated piles will last sufficiently longer than creosoted piles, the additional expense will be justified.

(c) Accurate records should be kept of randomly placed pile treatments and of installation and removal dates so that a better selection of treatments could be made."

APPENDIX C
GEOTEXTILE FILTER TESTS

1. Tensile Strength and Elongation Test

Test five Stronger Principal Direction (SPD) and five Weaker Principal Direction (WPD) samples, unaged, in accordance with ASTM Standard D 1682-64 Breaking Load and Elongation of Textile Fabric-Grab Test Method. The jaws shall be 2.54 centimeters (1 inch) square and the constant rate of travel 30.5 centimeters (12 inches) per minute. Care should be exercised to make sure the fabric is properly alined to the jaws. If not properly alined, the results will be inaccurate. Test should be conducted at 22.8° ±2° Celsius (73° ±3° Fahrenheit).

2. Seam Breaking Strength

Test five unaged samples in accordance with method ASTM Standard D 1683-68, using 2.54-centimeter square jaws and 30.5 centimeters per minute constant rate of travel.

3. Puncture Strength

Test five unaged samples using Standard ASTM D 751-73 and determine the puncture strength using the Tension Testing Machine With Ring Clamp, except that the steel ball should be replaced with a 5/16-inch diameter, solid steel cylinder centered within the ring clamp.

4. Burst Strength

Test five unaged samples in accordance with ASTM Standard D 751-73 and determine the bursting strength using the Diaphragm Test Method.

5. Abrasion Resistance

Test five SPD and five WPD unaged samples in accordance with ASTM Standard D 3884-80 (formerly D 1175-71) using the "Rotary Platform, Double Head" method. The abrasive wheels must be the rubber-base type equal to the CS-17 "Calibrase" manufactured by Taber Instrument Company. The load on each wheel must be 1 000 grams and the test must be continued for 1 000 revolutions. After abrasion determine the residual tensile strength by the 1-inch Ravelled Strip Method of ASTM D1682-64.

6. Freeze-Thaw Test

Subject five SPD and five WPD samples, 10.2 ±0.51 by 15.2 ±0.51 centimeters (4 ±0.2 by 6 ±0.2 inches), unaged, to 300 freeze-thaw cycles as described in test method CRD-C 20. Each cycle should be a duration of 2 hours ±4 minutes duration. Then test samples using ASTM Standard D 1682 Grab Test Method as described in 1. above.

7. High Temperature Test

Place five SPD and five WPD samples, 10.2 ±0.51 by 15.2 ±0.51 centimeters, unaged, in a forced draft oven at 82.2° ±2° Celsius (180° ±3° Fahrenheit) for 48 ±2 hours. Then test each sample at the test temperature using ASTM Standard D 1682 Grab Test Method as described in 1. above.

8. Low Temperature Test

Place five SPD and five WPD samples, 10.2 ±0.51 by 15.2 ±0.51 centimeters, unaged, in a refrigerator at -17.8° ±2° Celsius (0° ±3° Fahrenheit) for 48 ±2 hours, then test each sample at the test temperature using ASTM Standard D 1682 Grab Test Method as described in 1. above.

9. Acid Test

Submerge five SPD and five WPD samples, 10.2 ±0.51 by 15.2 ±0.51 centimeters, unaged, in a 1-liter glass beaker filled to within 5.1 centimeters (2 inches) of its top, with a solution of sufficient hydrochloric acid in about a liter of distilled water to produce a pH of 2 ±0.1. Cover the beaker with a watch glass and place in a constant temperature bath at 62.8° ±2° Celsius (145° ±5° Fahrenheit). Using a 0.635-centimeter glass tube inserted into the spouted beaker to within 1.27 centimeters of the beaker bottom, air is bubbled gently through the solution at the rate of one bubble per second continuously for 14 days. The solution should be changed every 24 hours, with the new warmed to 65.6° ±.5° Celsius (150° ±1° Fahrenheit) before replacing the old solution. Test each sample then for tensile strength and elongation using ASTM Standard D 1682 Grab Test Method as described in 1. above.

10. Alkali Test

Submerge five SPD and five WPD samples, 10.2 ±0.51 by 15.2 ±0.51 centimeters, unaged, in a 1-liter glass beaker filled to within 5.1 centimeters of its top, with a solution of equal amounts of chemically pure sodium hydroxide and potassium hydroxide dissolved in about a liter of distilled water to obtain a pH of 13 ±0.1. Cover the beaker with a watch glass and place in a constant temperature bath at 62.8° ±2° Celsius. Using a 0.635-centimeter glass tube inserted into the spouted beaker to within 1.27 centimeters of the beaker bottom, air is bubbled gently through the solution at the rate of one bubble per second continuously for 14 days. The solution should be changed every 24 hours, with the new solution warmed to 65.6° ±0.5° Celsius before replacing the old solution. Test each sample then for tensile strength and elongation using ASTM Standard D 1682 Grab Test Method as described in 1. above.

11. JP-4 Fuel Test

Submerge ten SPD and ten WPD samples, 10.2 ±0.51 by 15.2 ±0.51 centimeters, unaged, in JP-4 fuel at room temperature for 7 days. Test each sample then for tensile strength using ASTM Standard D 1682 Grab Test Method as described in 1. above.

12. Determination of Equivalent Opening Size (E.O.S.)

a. Calhoun Method, 1972. Based on the Calhoun (1972) method, five unaged samples shall be tested. Obtain about 150 grams of each of the following fractions of a sand composed of sound, rounded-to-subrounded particles:

U.S. Standard Sieve Number

Passing	Retained On	Passing	Retained On	Passing	Retained On
10	20	30	40	50	70
20	30	40	50	70	100
				100	120

The cloth shall be affixed to a standard sieve having openings larger than the coarsest sand used, in such a manner that no sand can pass between the cloth and the sieve wall. The sand shall be oven dried. Shaking shall be accomplished as described in EM 1110-2-1906, Appendix V, paragraph 2d(1)(g), except shaking shall be continued for 20 minutes. Determine by sieving (using successively coarser fractions) that fraction of sand of which 5 percent or less by weight passes the cloth; the equivalent opening size of the cloth sample is the "retained on" U.S. Standard Sieve number of this fraction.

b. Corps of Engineers 1977 Guide Specification Method. Five unaged fabric samples shall be tested. Obtain 50 grams of each of the following fractions of standard glass beads:

U.S. Standard Sieve Number

Designated EOS	Passing	Retained On	Designated EOS	Passing	Retained On
20	18	20	70	60	70
30	25	30	100	80	100
40	35	40	120	100	120
50	45	50			

Suitable glass beads can be obtained from:

Cataphote Division
Ferro Corporation
P.O. Box 2369
Jackson, Mississippi 39205
Telephone: (601) 939-4631

Within each size range, 98 percent of the beads should be within the specified range. The fabric shall be affixed to a standard sieve 8 inches in diameter having openings larger than the largest beads to be used in the test. The fabric shall be attached to the sieve in such a manner that no beads can pass between the fabric and the sieve wall. Shaking shall be accomplished as described in paragraph 2d(1)(g), Appendix V, EM 1110-2-1906, except the times for shaking shall be 20 minutes. Determine by sieving (using successively coarser fractions) that size of beads of which 5 percent or less by weight passes through the fabric; the equivalent opening size, EOS of the fabric sample is the "retained on" U.S. Standard Sieve number of this fraction.

13. Determination of Percent of Open Area (POA)

Each of five unaged samples should be placed separately in a 2 by 2-inch glass slide holder and the image projected with a slide projector on a screen. Select a block of 25 openings near the center of the image and measure to the nearest 25.4 micrometers (0.001 inch) the length and width of each of the 25 openings and the widths of two fibers adjacent to each opening. The percent open area is determined by dividing the sum of the open areas of the 25 openings by the sum of the total area of the 25 openings and their adjacent fibers.

14. Determination of Gradient Ratio (GR)

A constant head permeability test shall be performed in a permeameter cylinder on soil specimens representative in classification and density of those materials to be protected, and in accordance with EM 1110-2-1906, Appendix VII, with the following modifications:

(1) A piece of hardware cloth with 0.64-centimeter (0.25 inch) openings shall be placed beneath the filter fabric specimen to support it. The fabric and the hardware cloth shall be clamped between flanges so that no soil or water can pass around the edges of the cloth.

(2) The soil specimen shall have a length of 10.16 centimeters (4 inches). Piezometer taps shall be placed 2.54 centimeters below the fabric, and 2.54, 5.08, and 7.62 centimeters above the fabric.

(3) Tapwater shall be permeated through the specimen under a constant head loss for a continuous period of 24 hours. The tailwater level shall be above the top of the soil specimen. The gradient ratio shall be determined from the readings taken at the end of the 24-hour period.

(4) The gradient ratio is the ratio of the hydraulic gradient over the fabric and the 1 inch of soil immediately next to the fabric (i_1), to the hydraulic gradient over the 2 inches of soil between 1 and 3 inches above the fabric (i_2).

$$GR = \frac{i_1}{i_2}$$

APPENDIX D

INFORMATIONAL ORGANIZATIONS

Informational Sources

American Association of Port Authorities (AAPA)
1612 K Street, N.W.
Washington, D.C. 20006

American Concrete Institute
Box 19150 Redford Station
Detroit, Michigan 48219

American Institute of Timber Construction
333 W. Hampden Rd.
Englewood, Co 80110

American Wood Preservers Institute
1651 Old Meadow Road
McLean, Virginia 22101

National Association of Corrosion Engineers
P.O. Box 218346
Houston, Texas 77218

National Forest Products Association
1619 Massasschusetts Avenue, N.W.
Washington, D.C. 20036

Portland Cement Association
5420 Old Orchard Road
Skokie, Illinois 60077

The Asphalt Institute
Asphalt Institute Building
College Park, Maryland 20740

The Museum of Comparative Zoology
Harvard University
Cambridge, Mass. 02138

National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

The Sulphur Institute
1725 K Street, N.W.
Washington, D.C. 20006

U.S. Army Coastal Engineering Research Center
Kingman Building
Fort Belvoir, Virginia 22060

U.S. Department of Agriculture Forest Service
Forest Products and Engineering Research
P.O. Box 2417
Washington, D.C. 20013

U.S. Navy Bureau of Yards and Docks
Washington, D.C. 20390

APPENDIX E

GLOSSARY OF TERMS

ABRADED STRENGTH - The result when tested in accordance with ASTM D1682, "Breaking Load and Elongation of Textile Fabric, 1-Inch Ravelled Strip Method". One-inch square jaws at a constant rate of traverse of 12 inches per minute.

ABRASION RESISTANCE - The ability of a surface to resist wear by friction.

ALKALINE - The excess of hydroxyl ions over hydrogen ions. Seawater is usually alkaline.

ALKALINITY - The capacity of a water to accept protons, i.e., hydrogen ions. It is usually expressed as milliequivalents per liter.

ANAEROBIC - An oxygen-independent type of respiration.

ANNEAL - To subject to high heat, with subsequent cooling, so as to soften thoroughly and render less brittle.

ANODE - The positive pole or electrode of an electrolytic cell.

AQUATIC - Growing or living in, or frequenting, water as opposed to terrestrial.

ARMOR - The outer or exposed layer of material(s) (stones, blocks, etc.) in a protective structure subjected to attack by wave or scour forces.

AUSTENITIC - Having a solid solution of carbon or iron carbide in iron as a constituent of steel under certain conditions.

BANK - (1) The rising ground bordering a lake, river, or sea; of a river or channel, designated as right or left as it would appear facing downstream. (2) An elevation of the sea floor of large area, located on a Continental (or island) Shelf and over which the depth is relatively shallow but sufficient for safe surface navigation; a group of shoals. (3) In its secondary sense, a shallow area consisting of shifting forms of silt, sand, mud, and gravel, but in this case it is only used with a qualifying word such as "sandbank" or "gravelbank".

BASIN, BOAT - A naturally or artificially enclosed or nearly enclosed harbor area for small craft.

BATHYMETRY - The measurement of depths of water in oceans, seas, and lakes; also information derived from such measurements.

BAY - A recess in the shore or an inlet of a sea between two capes or headlands, not as large as a gulf but larger than a cove.

BEACH - The zone of unconsolidated material that extends landward from the low water line to the place where there is marked change in material or physiographic form, or to the line of permanent vegetation (usually the effective limit of storm waves). The seaward limit of a beach - unless otherwise specified - is the mean low water line.

BEACH EROSION - The carrying away of beach materials by wave action, tidal currents, littoral currents, or wind.

BENTHIC - Pertaining to the subaquatic bottom.

BENTHOS - A collective term describing: (1) Bottom organisms attached or resting on or in the bottom sediments. (2) Community of animals living in or on the bottom.

BIOASSAY - The use of living organisms as an index to determine environmental conditions.

BIOCHEMICAL OXYGEN DEMAND (BOD) - The amount of oxygen required by the biological population of a water sample to oxidize the organic matter in that water. It is usually determined over a 5-day period under standardized laboratory conditions and hence may not represent actual field conditions.

BIOLOGICAL RESISTANCE - Ability to resist degradation due to microorganisms.

BIOMASS - The amount of living material in a unit area for a unit time. Also standing crop, standing stock, live-weight.

BIOTA - The living part of a system (flora and fauna).

BOULDER - A rounded rock more than 10 inches in diameter; larger than a cobblestone. See SOIL CLASSIFICATION.

BOTTOM - The ground or bed under any body of water; the bottom of the sea.

BREAKER - A wave breaking on a shore, over a reef, or other feature.

BREAKWATER - A structure protecting a shore area, harbor, anchorage, or basin from waves.

BULKHEAD - A structure or partition to retain or prevent sliding of the land. A secondary purpose is to protect the upland against damage from wave action.

BUOY - A float; especially a floating object moored to the bottom, to mark a channel, anchor, shoal, rock, etc.

BUOYANCY - The resultant of upward forces, exerted by the water on a submerged or floating body, equal to the weight of the water displaced by this body.

BURST STRENGTH - The resistance of a fabric to rupture due to pressure applied at right angles to the plane of the fabric under specified conditions, usually expressed as the pressure causing failure. Burst is due to tensile failure of the fabric.

CATHODE - The negative pole or electrode of an electrolytic cell.

CAUSEWAY - A raised road, across wet or marshy ground, or across water.

CHANNEL - (1) A natural or artificial waterway of perceptible extent which either periodically or continuously contains moving water, or which forms a connecting link between two bodies of water. (2) The part of a body of water deep enough to be used for navigation through an area otherwise too shallow for navigation. (3) A large strait, as the English Channel. (4) The deepest part of a stream, bay, or strait through which the main volume or current of water flows.

CLAY - A fine grained soil with cohesive strength inversely related to water content. It is plastic when moist and hardens when baked or fired. See SOIL CLASSIFICATION.

CLIFF - A high, steep face of rock; a precipice.

CLOGGING - The phenomena causing either a reduction in, or the elimination of, the permeability of the filter.

COAST - A strip of land of indefinite width (may be several miles) that extends from the shoreline inland to the first major change in terrain features.

COASTAL AREA - The land and sea area bordering the shoreline.

COBBLE (COBBLESTONE) - A naturally rounded stone larger than a pebble, especially one 6 inches to a foot in diameter.

COLLECTOR PIPE - A pipe capable of collecting and carrying water from the soil.

COLONIZATION - A natural phenomenon where a species invades an area previously unoccupied by that species and becomes established. To be successful the species must be able to reproduce in that area.

CONTOUR - A line on a map or chart representing points of equal elevation with relation to a DATUM. It is called an ISOBATH when connecting points of equal depth below a datum.

CORAL - (1) (Biology) Marine coelenterates (Madreporia), solitary or colonial, which form a hard external covering of calcium compounds, or other materials. The corals which form large reefs are limited to warm, shallow waters, while those forming solitary, minute growths may be found in colder waters to great depths. (2) (Geology) The concretion of coral polyps, composed almost wholly of calcium carbonate, forming reefs, and treelike and globular masses. May also include calcareous algae and other organisms producing calcareous secretions, such as bryozoans and hydrozoans.

CORE - A vertical cylindrical sample of the bottom sediments from which the nature and stratification of the bottom may be determined. The interior material of a breakwater or groin.

CREEP - To slip or become slightly displaced; specifically of metal to shift longitudinally under weight.

CURE - To alter industrially, as to vulcanize (rubber) or to treat (synthetic resins) with heat or chemicals to make infusible.

CURRENT - A flow of water.

CURRENT, LITTORAL - Any current in the littoral zone caused primarily by wave action, e.g., longshore current, rip current.

DAP - A notch cut in one timber to receive another, usually permitting the two timbers to be flush.

DATUM, PLANE - The horizontal plane to which soundings, ground elevations, or water surface elevations are referred. The plane is called a TIDAL DATUM when defined by a certain phase of the tide. The following datums are ordinarily used on hydrographic charts:

MEAN LOW WATER - Atlantic coast (U.S.), Argentina, Sweden, and Norway;
MEAN LOWER LOW WATER - Pacific coast (U.S.);
MEAN LOW WATER SPRINGS - United Kingdom, Germany, Italy, Brazil, and Chile;
LOW WATER DATUM - Great Lakes (U.S. and Canada);
LOWEST LOW WATER SPRINGS - Portugal;
LOW WATER INDIAN SPRINGS - India and Japan;
LOWEST LOW WATER - France, Spain, and Greece.

A common datum used on topographic maps is based on MEAN SEA LEVEL.

DENIER - A unit expressing the fineness of silk, rayon, nylon or other synthetic yarns in terms of weights in grams per 9 000 meters of length.

DEPTH - The vertical distance from a specified tidal datum to the sea floor.

DIKE (DYKE) - A wall or mound built around a low-lying area to prevent flooding.

DOLPHIN - A cluster of piles.

DUNES - (1) Ridges or mounds of loose, wind-blown material, usually sand. (2) BED FORMS smaller than bars but larger than ripples that are out of phase with any water-surface gravity waves associated with them.

DURABILITY - A relative term for the resistance of a material to loss of physical properties or appearance as a result of wear or dynamic operation.

ELONGATION AT FAILURE - The length of a fabric test specimen when it is broken in a tensile test (ASTM D1682-64) compared to its original length, expressed as a percent.

EMBANKMENT - An artificial bank such as a mound or dike, generally built to hold back water or to carry a roadway.

ENDEMIC - Native to a specific geographic area.

EQUIVALENT OPENING SIZE - E.O.S. - The number of a U.S. standard sieve having openings closest in size to the diameter of uniform particles which will have 95 percent by weight retained by the fabric when shaken in a prescribed manner.

EROSION - The wearing away of land by the action of natural forces. On a beach, the carrying away of beach material by wave action, tidal currents, littoral currents, or by deflation.

ESTUARY - (1) The part of a river that is affected by tides. (2) The region near a river mouth in which the freshwater of the river mixes with the saltwater of the sea.

FAUNA - Animal life as opposed to flora (plant life). Generally the entire group of animals found in an area.

FIBRILLATED YARN - Yarns formed of fibers from sheet plastic film.

FILAMENT - A single thread (yarn) of extreme length.

FILL - Fibers or yarns placed at right angles to the warp.

FILTER FABRIC - A permeable fabric of synthetic fibers whose function is to retain soil and be permeable to water.

FLORA - Plant life as opposed to fauna (animal life). The entire group of plants found in an area.

FORESHORE - The part of the shore lying between the crest of the seaward berm (or upper limit of wave wash at high tide) and the ordinary low water mark, that is ordinarily traversed by the uprush and backrush of the waves as the tides rise and fall.

FOULING ORGANISM - An organism that attaches to the surface of submerged or introduced objects regardless of whether the objects are natural or man-made.

GALVANIZE - To subject to the action of electric currents; to coat with zinc.

GEOTEXTILE - Any permeable textile used with foundations, soils, rock, earth or any other geotechnical material as an integral part of a man made project, structure or system.

GEOTEXTILE FILTER - A permeable fabric of synthetic fibers whose function is to retain soil and be permeable to water.

GRAVEL - A coarse grained, cohesionless material whose size ranges between 76.2 millimeters and the No. 4 sieve. See SOIL CLASSIFICATION.

GROIN (British, GROYNE) - A shore protection structure built (usually perpendicular to the shoreline) to trap littoral drift or retard erosion of the shore.

GROUND WATER - Subsurface water occupying the zone of saturation. In a strict sense, the term is applied only to water below the WATER TABLE.

GULF - A large embayment in a coast; the entrance is generally wider than the length.

HABITAT - The place where an organism lives.

HARBOR (British, HARBOUR) - Any protected water area affording a place of safety for vessels.

HEAT BONDED - The fabric web is subjected to a relatively high temperature. The filaments are welded together at the contact points.

HEAT OF HYDRATION - The heat evolved or absorbed when hydration occurs; specifically, when water is added to a calcium aluminate powder to produce cement.

IMPERMEABLE GROIN - A groin through which sand cannot pass.

INTERLOCKING CONCRETE BLOCK - A cast or machine produced concrete block having interengaging or overlapping edges.

JETTY - (1) (U.S. usage) On open seacoasts, a structure extending into a body of water, and designed to prevent shoaling of a channel by littoral materials, and to direct and confine the stream or tidal flow. Jetties are built at the mouth of a river or tidal inlet to help deepen and stabilize a channel. (2) (British usage) Jetty is synonymous with "wharf" or "pier".

LARVA - A sexually immature form of any animal unlike its adult form and requiring changes before reaching the basic adult form.

LITTORAL - Of or pertaining to a shore, especially of the sea.

LITTORAL DRIFT - The sedimentary material moved in the littoral zone under the influence of waves and currents.

LITTORAL TRANSPORT - The movement of littoral drift in the littoral zone by waves and currents. Includes movement parallel (longshore transport) and perpendicular (onshore-offshore transport) to the shore.

LONGSHORE - Parallel to and near the shoreline.

MONOFILAMENT - A single filament of a manmade fiber, usually of a DENIER higher than 15.

MULTIFILAMENT - A yarn consisting of many continuous filaments or strands.

MUD - A fluid-to-plastic mixture of finely divided particles of solid material and water.

NONWOVEN FABRIC - A textile structure produced by bonding or interlocking of fibers, or both, accomplished by mechanical, chemical or solvent means and combinations thereof excluding woven and knitted fabrics.

NOURISHMENT - The process of replenishing of beach. It may be brought about naturally, by longshore transport, or artificially by the deposition of dredged materials.

NYLON FIBER - A manufactured fiber in which the fiber-forming substance is any long chain synthetic polyamide having recurring amide groups (-NH-CO-) as an integral part of the polymer chain.

OFFSHORE - (1) In beach terminology, the comparatively flat zone of variable width, extending from the breaker zone to the seaward edge of the Continental Shelf. (2) A direction seaward from the shore.

ONSHORE - A direction landward from the sea.

ORGANISM - Any living individual whether plant or animal.

OUTFALL - A structure extending into a body of water for the purpose of discharging sewage, storm runoff, or cooling water.

OVERTOPPING - Passing of water over the top of a structure as a result of wave runup or surge action.

PERCENT OPENING AREA (POA) - The visible net area of a fabric that is available for water to pass through the fabric, normally determinable only for woven and nonwoven fabrics having distinct visible and measurable openings that continue directly through the fabric.

PERMEABLE GROIN - A groin with openings large enough to permit passage of appreciable quantities of littoral drift.

PIER - A structure, usually of open construction, extending out into the water from the shore, to serve as a landing place, a recreational facility, etc., rather than to afford coastal protection. In the Great Lakes, a term sometimes improperly applied to jetties.

PILE - A long, heavy timber or section of concrete or metal to be driven or jetted into the earth or seabed to serve as a support or protection.

PILE, SHEET - A pile with a generally slender flat cross section to be driven into the ground or seabed and meshed or interlocked with like members to form a diaphragm, wall, or bulkhead.

PILING - A group of piles.

PIPING - The process by which soil particles are washed in or through pore spaces in drains and filters.

PLASTIC FILTER - See Filter Fabric.

PLASTIC FILTER FABRIC - See Filter Fabric.

POLYAMIDE - See Nylon Fiber.

POLYETHYLENE FIBER - A manufactured fabric in which the fiber-forming substance is an olefin made from polymers or copolymers of ethylene.

POLYMER - A high molecular chainlike structure from which manmade fibers are derived; produced by linking together molecular units called monomers - consisting predominantly of nonmetallic elements or compounds.

POLYPROPYLENE FIBER - A manufactured fiber in which the fiber-forming substance is an olefin made from polymers or copolymers of propylene.

POLYESTER FIBER - A manufactured fiber in which the fiber-forming substance is any long chain synthetic polymer composed of at least 85 percent by weight of an ester of dihydric alcohol and terephthalic acid (FTC).

POLYVINYLIDENE CHLORIDE FIBER - A manufactured fiber in which the fiber-forming substance is a thermoplastic derived by copolymerization of two or more vinyl monomers.

PORT - A place where vessels may discharge or receive cargo; may be the entire harbor including its approaches and anchorages, or may be the commercial part of a harbor where the quays, wharves, facilities for transfer of cargo, docks, and repair shops are situated.

POZZOLAN - A siliceous rock of volcanic origin, first found near Puteoli (modern Pozzuoli), Italy, used in preparing a hydraulic cement.

PRECAST CELLULAR BLOCK - A cast or machine produced concrete block having continuous void(s) through the vertical plane. Normally with smooth vertical or near vertical sides (not interlocking). Some are cabled together horizontally to form a mat.

PUNCTURE RESISTANCE - Resistance to failure of a fabric due to a blunt object applying a load over a relatively small area. Failure is due to tensile failure of the fibers.

QUARRYSTONE ARMOR UNITS - Relatively large quarrystones that are selected to fit specified geometric characteristics, including compact dimensional proportions and a nearly uniform size, usually large enough to require individual placement. In normal cases they are placed in a layer at least two stones thick.

QUAY - (Pronounced KEY) - A stretch of paved bank, or a solid artificial landing place parallel to the navigable waterway, for use in loading and unloading vessels.

RESIN BONDED - The fabric web is impregnated with a resin which serves to coat and cement the fibers together.

REVETMENT - A facing of stone, concrete, etc., built to protect a scarp, embankments, or shore structure against erosion by wave action or currents.

RHEOLOGY - Science dealing with the deformation and flow of matter.

RIPRAP - A protective layer or facing of quarrystone randomly placed to prevent erosion, scour, or sloughing of an embankment or bluff toe, also the stone so used, usually well graded within wide size limits. The quarrystone is placed in a layer at least twice the thickness of the 50-percent size stone or 1.25 times the thickness of the largest size stone in the size gradation.

RUBBLE - (1) Loose angular waterworn stones along a beach. (2) Rough, irregular fragments of broken rock.

RUBBLE-MOUND STRUCTURE - A mound of random-shaped and random-placed stones protected with a cover layer of selected stones or specially shaped concrete armor units. (Armor units in primary cover layer may be placed in orderly manner or dumped at random.)

RUNUP - The rush of water up a structure or beach on the breaking of a wave. Also UPRUSH. The amount of runup is the vertical height above stillwater level that the rush of water reaches.

SAND - An earthy matrial whose grain size is between 4.76 and 0.075 millimeters. Within this classification sand may vary from coarse to fine. Sand is cohesionless but exhibits appearance of cohesion when wet. See SOIL CLASSIFICATION.

SANDCORE JETTY - A jetty, groin or breakwater in which the core material consists of sand rather than stone.

SARAN - See polyvinylidene chloride fiber.

SCREED - A strike board used to level or strike off concrete pavement slabs or cushion courses for block pavements.

SCOUR - Removal of underwater material by waves and currents, especially at the base or toe of a shore structure.

SCOUR PROTECTION - The protection at the base or toe of a structure to prevent removal of underwater material by waves and currents.

SEAWALL - A structure separating land and water areas, primarily designed to prevent erosion and other damage due to wave action. See also BULKHEAD.

SEICHE - (1) A standing wave oscillation of an enclosed water body that continues, pendulum fashion, after the cessation of the originating force, which may have been either seismic or atmospheric. (2) An oscillation of a fluid body in response to a disturbing force having the same frequency as the natural frequency of the fluid system. Tides are now considered to be seiches induced primarily by the periodic forces caused by the sun and moon. (3) In the Great Lakes area, any sudden rise in the water of a harbor or a lake whether or not it is oscillatory. Although inaccurate in a strict sense, this usage is well established in the Great Lakes area.

SEISMIC SEA WAVE (TSUNAMI) - A long-period wave caused by an underwater seismic disturbance or volcanic eruption. Commonly misnamed "tidal wave."

SHEAR FRACTURE - An action or stress resulting from applied forces, which causes or tends to cause two contiguous parts of a body to slide relatively to each other in a direction parallel to their plane of contact.

SHEET PILE - See PILE, SHEET.

SHOAL (noun) - A detached elevation of the sea bottom, comprised of any material except rock or coral, which may endanger surface navigation.

SHOAL (verb) - (1) To become shallow gradually. (2) To cause to become shallow. (3) To proceed from a greater to a lesser depth of water.

SHORE - The narrow strip of land in immediate contact with the sea, including the zone between high and low water lines. A shore of unconsolidated material is usually called a beach.

SHORELINE - The intersection of a specified plane of water with the shore or beach. (e.g., the high water shoreline would be the intersection of the plane of mean high water with the shore or beach.) The line delineating the shoreline on National Ocean Survey nautical charts and surveys approximates the mean high water line.

SHOTCRETE - A pneumatically applied concrete or grout.

SILT - A fine grained soil of low plasticity which may exhibit an apparent cohesion due to capillary forces. See SOIL CLASSIFICATION.

SLOPE - The degree of inclination to the horizontal. Usually expressed as a ratio, such as 1:25 or 1 on 25, indicating 1 unit vertical rise in 25 units of horizontal distance; or in a decimal fraction (0.04); degrees (2^{o} 18'); or percent (4%).

SLUMP - To fall or sink suddenly.

SOIL CLASSIFICATION (size) - An arbitrary division of a continuous scale of grain sizes such that each scale unit or grade may serve as a convenient class interval for conducting the analysis or for expressing the results of an analysis.

SPALL - To breakup or reduce by chipping with a hammer; to chip or crumble.

SPECIES - An aggregate of interbreeding populations that under natural conditions is reproductively isolated.

SPLASH ZONE - The zone immediately landward of the mean higher high water level affected by the wave spray.

STONE, DERRICK - Stone heavy enough to require handling individual pieces by mechanical means, generally 1 ton and up.

STRENGTH - Load capacity at failure. Depending on the usage, load may be expressed in stress, force per unit width, or force.

SURF ZONE - The area between the outermost breaker and the limit of wave uprush.

TENSILE STRENGTH - The strength shown by a material subjected to tension as distinct from torsion, compression or shear.

TERRESTRIAL - Of or relating to the earth and its inhabitants as opposed to aquatic.

THIXOTROPIC - Becomes fluid when shaken, stirred, or otherwise disturbed and sets again to a gel when allowed to stand.

TOE - The lower elevation terminus of a revetment or side slopes of a groin, breakwater or jetty. The outer limit of a scour protection mound.

TREMIE - An apparatus for depositing and consolidating concrete under water consisting essentially of a tube of wood or sheet metal with a top in the form of a hopper.

TSUNAMI - A long-period wave caused by an underwater disturbance such as a volcanic eruption or earthquake. Commonly miscalled "tidal wave."

TURBIDITY - A condition where transparency of water is reduced. It is an optical phenomenon and does not necessarily have a direct linear relationship to particulate concentration.

ULTRAVIOLET (UV) RESISTANCE - Ability to resist deterioration on exposure to sunlight.

VERTICAL SEAWALL - See Bulkhead.

VISCOSITY - (or internal friction) - That molecular property of a fluid that enables it to support tangential stresses for a finite time and thus to resist deformation.

WARP - Fibers or yarns lengthwise in the fabric.

WEB - The sheet or mat of fibers or filaments before bonding or needle-punching to form a nonwoven fabric.

WHARF - A structure built on the shore of a harbor, river, or canal, so that vessels may lie alongside to receive and discharge cargo and passengers.

WOVEN FABRIC - A textile structure comprising two or more sets of filaments or yarns interlaced in such a way that the elements pass each other essentially at right angles and one set of elements is parallel to the fabric axis. Usually has a uniform pattern with distinct and measurable openings. Commonly referred to as cloth.

YARN - A generic term for a continuous strand of textile fibers, filaments or materials in a form suitable for weaving or otherwise intertwining to form a textile fabric.

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